Photoproduction of neutral kaons on the deuteron near the threshold

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Chapter 1

Introduction

1.1 Strangeness production

Strangeness photo-/electro-production is not only of interest itself but also the useful probe into the investigation of hadronic interaction, hadron structure etc [1]. Recent two topics are exemplified below.

In the study of the expansion of NN-interaction so as to include the baryons with a degrees-of-freedom of strangeness, that is the YN-interaction, the hypernuclear spectroscopy holds an important position since the nucleon-hyperon scattering experiments are practically difficult. Thus, the spectroscopy of the hypernuclei can provide informations of the effective YN-interaction in nuclei, in which the energy resolution is crucially important to derive the seperation of binding energy among states. The resolution have reached down 2 MeV (FWHM) in ($\pi^+, K^+$) reaction[2, 3] using SKS (Super conducting Kaon Spectrometer, [4]) at KEK. The more higher resolution is expected in the ($e, e' K^+$) reaction using the high quality continuous electron beam at CEBAF, and to be 500 keV[5]. This reaction which is raised by virtual photon selectively populates angular-momentum stretched states for all of the $\Lambda$ orbits as well as ($\pi^+, K^+$) reaction due to large momentum transfer. Besides the spin-flip amplitude is large because the photon carries spin 1. The ($\pi^+, K^+$) reaction converts a neutron into a $\Lambda$, in contrast the ($e, e' K^+$) reaction converts a proton into $\Lambda$. Therefore both reaction is mirror reaction each other, and the generated hypernucleus is also mirror state using the $Z=N$ target. However, since the interactions in ($e, e' K^+$) reaction is electro-magnetic production of strangeness, we must have the reliable knowledge of the interaction itself.

The search for, so-called, missing resonances is another subject in the investigation of photo- and electro-production of strangeness. These resonances have been predicted by QCD models that contain three constituent valence quarks but not validated experimentally in the hadronic reaction such a $\pi N$. A reasonable explanation of this is that these resonances are coupled except to $\pi N$, such as a $K\Lambda$ channel. For example, in the $p(\gamma, K^+)\Lambda$ reaction, new experimental data shows the bump structure around $W = 1.9$ GeV in the energy dependence of total cross section[6], and Mart et al. implies that the bump structure can be explained by introducing a $D_{13}(1900)$[7] which is one of the missing resonances. It is believed that strangeness production can be a good probe to find unexplored resonances states.
The elementary processes of strangeness photoproduction are not well known as explained below, and $n(\gamma, K^0)\Lambda$ reaction plays an essential role to clarify the strangeness photoproduction.

1.1.1 Experimental investigation

The strangeness photoproduction contains 6 channels as follows,

<table>
<thead>
<tr>
<th>process</th>
<th>threshold photon energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma p \rightarrow K^+\Lambda$</td>
<td>911.1</td>
</tr>
<tr>
<td>$\gamma p \rightarrow K^+\Sigma^0$</td>
<td>1046.1</td>
</tr>
<tr>
<td>$\gamma p \rightarrow K^0\Sigma^+$</td>
<td>1047.5</td>
</tr>
<tr>
<td>$\gamma n \rightarrow K^0\Lambda$</td>
<td>915.4</td>
</tr>
<tr>
<td>$\gamma n \rightarrow K^0\Sigma^0$</td>
<td>1052.1</td>
</tr>
<tr>
<td>$\gamma n \rightarrow K^+\Sigma^-$</td>
<td>1050.5.</td>
</tr>
</tbody>
</table>

The first generation of the investigations of strangeness photo-production had been carried out until the late 1950s. The data measured for the $p(\gamma, K^+){\Lambda}$ reaction from threshold up to 1.4 GeV contained the differential cross section [8, 9, 10, 11, 12, 13], total cross section [14], final state $\Lambda$ polarization [10, 12] and polarized target [15]. In addition, the measurements with higher energy [16] and those of electro-production [17, 18] were executed. However, precise measurements at high energy, those of polarization and those of other strangeness production channels were still to be conducted at that time.

Since 1990s, new experiment at the accelerator facility with a photon or electron beam, JLab(CLAS) [19, 20], ELSA(SAPHIR) [6, 21] and SPring-8(LEPS) [22], have worked.

The total and differential cross sections and the hyperon polarizations of $p(\gamma, K^+){\Lambda}$ and $p(\gamma, K^+){\Sigma^0}$ reactions were measured by SAPHIR [6] with much higher quality than before. Photon energy was from 0.8 to 2.6 GeV. This data lead into the missing resonance interpretation as mentioned above. In this experiment, the cross section of $p(\gamma, K^0){\Sigma^+}$ reaction was also measured, but the statistics were poor. Moreover, the following experiment was also carried out with extended photon energy range, from 0.85 to 2.65 GeV [21], and the further improved data were provided.

The transferred polarization in the exclusive $p(\bar{e}, K^+){\Lambda}$ reaction was measured by CLAS for the first time in the energy range. They reported that the kaon angular dependence of the transferred $\Lambda$ polarizations was not reproduced by the calculations from recent some models [19]. The group measured also the $p(\gamma, K^+){\Lambda}$ reaction in the photon energies from 0.911 to 2.325 GeV and reported that the bump structure appeared as well as the result taken by SAPHIR. However, the magnitude of the cross sections were systematically larger than SAPHIR data at forward angle.

The beam polarization asymmetries for the $p(\bar{\gamma}, K^+){\Lambda}$ and $p(\bar{\gamma}, K^+){\Sigma^0}$ reaction at LEPS. The photon energy was from 1.5 to 2.4 GeV. The asymmetries for both reaction are positive, and not reproduced by the theoretical calculations [22].
1.1.2 Theoretical analysis

There are various approaches to describe the elementary photoproduction of strangeness. The isobar models which describe the kaon photoproduction processes in terms of hadronic degrees of freedom using effective Lagrangian approach are suitable for a reliable calculation method as the further application. Regge model [23] is appropriate for the higher photon energy region, $E_\gamma \gtrsim 4$ GeV. Quark models [24] should be important; Although the chiral constituent quark formalism which allows us to introduce the all known resonances is able to relate the photoproduction data directly to the internal structure of the baryon resonances. It is embodied in non-relativistic formalism and so cannot be applied to the electroproduction process.

The isobar models are based on the Feynman diagrammatic technique in tree levels, which include the Born terms and exchanges of resonances as intermediate states. Figure 1.1 shows the Feynman diagrams for the isobar model. In this approach, every intermediate particle is treated as an effective field with its characteristic mass, photocoupling amplitude and strong decay width. The coupling constants for each resonances are not determined by the theory itself and treated as free parameters to be fitted by the experimental data.

For the Born terms, the coupling constants, $g_{K\Lambda p}, g_{K\Sigma^0p}$ are related to the $g_{\pi NN}$ assuming SU(3) flavor symmetry. For the 20% braking of the SU(3) symmetry due to the heavy constituent mass of s-quark, the $g_{K\Lambda p}, g_{K\Sigma^0p}$ are set within

\[-4.5 < g_{K\Lambda p}/\sqrt{4\pi} < -3.0 \quad (1.1)\]

\[0.9 < g_{K\Sigma^0p}/\sqrt{4\pi} < 1.3, \quad (1.2)\]

respectively, in recent models [25]. For nucleon resonances, there are too large number of possible combinations of resonances with mass smaller than 2 GeV/c due to the absence of dominant states. Therefore, the constraints, crossing symmetry [26, 27] and duality hypothesis [26], are assumed so as to reduce the number of resonances in models.

Historically, the isobar model for kaon photoproduction started 40 years ago with pioneering work by Thom [28], in which Feynman diagrams for Born terms and partial wave amplitudes for the resonances were used. However the theoretical analysis made little progress for almost 2 decade since his work due to the lack of experimental data.

Adelseck et al. constructed a refined model using diagrammatic techniques for the resonant terms as well as the Born terms [29]. This framework assured the relativistic invariance in the model. In the following decade, many theoretical models were suggested [25, 26, 27, 30, 31, 32, 33, 34]. At that time, new accelerators and detectors...
had been constructed and new experimental projects just started (Sect.1.1.1). Such experimental conditions triggered off the progress of the theoretical investigations.

In older models, there are some models not imposing the SU(3) conditions (eq.1.1,1.2), and other models not taking wrong phase relations although various models were proposed. Recently, most of the models are constructed to satisfy the condition. However, as far as the SU(3) symmetry is realized to the two main coupling constants, the contribution of the Born terms is nonphysically large[35]. To reduce this contribution, hyperon resonances or hadronic form factors, or a combination of both must be added. In this paper, the Kaon-MAID[36] and the Sacray-Lyon A (SLA) model[34], which are the latest theoretical models, are compared with the experimental data. The hadronic form factors are included in the Kaon-MAID models with the manner preserving gauge invariance. For the gauge invariance and current conservation, the extra contact term(Fig. 1.1(d)) must be introduced[37].

In Kaon-MAID, 4 N* and 2 Δ (for KΣ channel) in s-channel and K* and K_1 in t-channel are included. Specifically, the missing resonance D_{13}(1900)[7] is added, which is needed to reproduce the bump structure around W = 1900 MeV of the total cross section of K^+ photoproduction data by SAPHIR group[6] without hyperon resonances in u-channel. The missing resonance have not be observed in pion induced and pion photoproduction reaction but its existence was predicted by the constituent quark model[38].

On the other hand, the SLA takes into account 1 N* in s-channel, K* and K_1 in t-channel and 4 hyperon resonances in u-channel. The details of two models are described in Sect. 4.2.

These two models reproduce well the cross section of K^+ photoproduction since the parameters are adjusted from those data.

1.2 Purpose of the present study

As described in Sect. 1.1.1 and 1.1.2, strangeness photoproduction process have been studying mainly through the p(γ, K)Λ, Σ reaction. In contrast, n(γ, K^0)Λ process near the threshold has following features,

- Since no charge is involved in the reaction, the Born term in t-channel does not contribute,

- The sign of the coupling constant of Σ^0 exchange term in u-channel is opposite to the p(γ, K^+)Λ reaction from isospin symmetry, that is \( g_{K^0Σ^0n} = -g_{K^+Σ^0p} \).

These characteristics result that the effects of interference among diagrams are quite different from those of the K^+Λ production process. Besides the influence from the higher mass resonances is considered to be small near the threshold. Therefore, this reaction plays an unique role to investigate the strangeness photoproduction mechanism by comparing with K^+ production data. Figure 1.2 show the elementary cross section for K^+Λ and K^0Λ photoproduction. For K^+ production, both the energy dependence and angular distribution agree with each other. It is natural because the models are adjusted to reproduce the K^+ production data.
However, for $K^0$ production, the cross sections are quite differently. This implies that the $K^0$ photoproduction process can give additional the strangeness photoproduction. On calculating for the $K^0$ production using SLA, the coupling constants of the $K_1$ exchange terms in t-channel are not fixed in the model and free parameter. In figure 1.2, the value which is derived in Kaon-MAID model frame work is assumed for SLA ($r_{K_1K\gamma} = -1.6$, see Sect. 4.2).

![Graphs](image)

Figure 1.2: Elementary cross section for $K^+\Lambda$ (upper) and $K^0\Lambda$ (lower) photoproduction in terms of the energy dependence(left) and angular distribution(right). The solid(dashed) curves are calculated from the Kaon-MAID(SLA($r_{K_1K\gamma} = -0.4474$)).

Hence, we carried out the experiment of the $K^0$ photoproduction on deuteron target in the threshold region. We had carried out the pioneering experiment on a carbon target, and analyzed $K^0$ production via the quasi-free process[39]. The purpose of the present experiment is investigation of the strangeness elementary reaction.

The present thesis is arranged by the following order. Firstly, the experimental method and apparatus is described in Chapter 2. Secondly, the details of analysis are presented in Chapter 3. In Chapter 4, the experimental results and comparison with the theoretical calculations based on the Kaon-MAID and SLA are discussed. Finally, conclusion is given in Chapter 5.
Chapter 2

Experiment

In this chapter, experimental method and apparatus are described. The basic idea to measure \( K^0 \)s is discussed in Sect. 2.1.

In this experiment, \( K^0 \)s were measured in \( \pi^+\pi^- \) decay channel by Neutral Kaon Spectrometer (NKS) which was developed in the Laboratory of Nuclear Science of Tohoku University (LNS-Tohoku). The detectors system is described in Sect. 2.3. This experiment was carried out using 1 GeV photon beam at the second experimental hall in LNS-Tohoku. The photon beam is generated via bremsstrahlung and tagged by STB-tagger system, which is explained in Sect. 2.2.

In order to investigate \( K^0 \) elementary production process, the liquid deuterium target was used. The target system was developed for this experiment and provided the stable liquid state deuterium during experimental period as described in Sect. 2.4.

Online trigger condition and data acquisition system are explained in Sect. 2.5. In Sect. 2.6, data sets obtained in the present study are summarized.

2.1 Method

We measured \( n(\gamma, K^0)A \) process on a deuteron. Because both \( K^0 \) and \( \bar{K^0} \) have same decay modes, generated \( K^0 \) can change to \( \bar{K^0} \), e.g. via 2\( \pi \) or 3\( \pi \) as intermediate state.

\[
K^0 \leftrightarrow \left\{ \frac{2\pi}{3\pi} \right\} \leftrightarrow \bar{K^0}
\]

In the view of quark diagram, \( K^0 \) and \( \bar{K^0} \) are mixed via so-called box diagrams,
Although $K^0$ and $\bar{K}^0$ are not eigenstate of CP, final states of $2\pi$ and $3\pi$ are CP eigenstates,

\[
CP|\pi\pi> = +1 \cdot |\pi\pi>
\]
\[
CP|\pi\pi\pi> = -1 \cdot |\pi\pi\pi>
\]

In the assumption CP conservation in weak interaction, initial state of decay should be also eigenstate of CP. Such states are made of linear combination of $K^0$ and $\bar{K}^0$ as follows,

\[
|K_S^0> = \frac{1}{\sqrt{2}} (|K^0> - |\bar{K}^0>) \quad CP|K_S^0> = +1 \cdot |K_S^0>
\]
\[
|K_L^0> = \frac{1}{\sqrt{2}} (|K^0> + |\bar{K}^0>) \quad CP|K_L^0> = -1 \cdot |K_L^0>
\]

where the phase of $|K^0>$ is chosen so that $C|K^0> = +1 \cdot |K^0>$.

When $K^0$ is generated, its state is also described as linear combination of $K_S^0$ and $K_L^0$. Therefore, the probability of measuring $K^0$ as $K_S^0$ is 50%. The life time of $K_L^0$ which decay into 3 pions is longer than that of $K_S^0$ because the phase space of 3 pions is smaller than that of 2 pions. Table 2.1 shows the properties of both $K_S^0$ and $K_L^0$.

We detected the $K^0$ via the $K_S^0 \to \pi^+\pi^-$ decay channel.

### Table 2.1: Property of $K^0$.

<table>
<thead>
<tr>
<th></th>
<th>$K_S^0$</th>
<th>$K_L^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>497.648 MeV/c²</td>
<td></td>
</tr>
<tr>
<td>$c\tau$</td>
<td>2.67 cm</td>
<td>15.5 m</td>
</tr>
<tr>
<td>main decay mode</td>
<td>$\pi^+\pi^-$ (68.6 %)</td>
<td>$3\pi^0$ (21.1 %)</td>
</tr>
<tr>
<td></td>
<td>$2\pi^0$ (31.4 %)</td>
<td>$\pi^+\pi^-\pi^0$ (12.5 %)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\pi^±\mu^±\nu_\mu$ (27.2 %)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\pi^±e^±\nu_e$ (38.8 %)</td>
</tr>
</tbody>
</table>

### 2.2 Tagged photon beam at Laboratory of Nuclear Science (LNS)

LNS is one of a few laboratories providing the photon beam with energy of around 1 GeV. Figure 2.1 shows the schematic view of the experimental hall. The 200 MeV electron beam from LINAC is injected to 1.2 GeV STrecher Booster (STB) ring and boosted up to 1.2 GeV, and kept for 20 sec in the ring.

The photon is generated via bremsstrahlung and an scattered electron is tagged by STB-Tagger. Figure 2.2 shows the schematic view of STB-Tagger.

The STB-Tagger is an internal tagging system and located at one bending corner, which consists of 11µmϕ carbon string radiator, an analyzing magnet, 50 segments of finger plastic scintillators (TagF) and 12 segments of backup counter (TagB).
Because tagger counters are located nearly circulating electron beam, large backgrounds exist. The trajectory of these background is not the same with that of scattered electron from the radiator, therefore the coincidence between TagF and TagB is required. One backup counter corresponds to 4 finger counters in coincidence logic. Details for the trigger logic are explained in Sect.2.5.2 and for analysis in Sect.3.3.

The STB-Tagger system can provide uniform intensity photon beam tagged from 0.8 to 1.1 GeV by moving the radiator according to the remaining current of the circulated electron beam. When the radiator moves, the orbit of the scattered electron is changed. Therefore, the moved length of radiator is limited so that the shift of arrival points of scattered electrons are less than the half width of a tagger counter.

Figure 2.3 shows the beam cycle. The beam intensity was adjusted about 2~3 mA so that summation of the counting rate of tagger counters was about 2~3 MHz. From the limit of drift length of radiator and the

The energy calibration was carried out before, and so the correlation between a segment of TagF and photon energy was estimated.

Number of tagged photons are counted by scaler in each segment of TagF. The method to estimate the number photon bombarded on target is described in Sect.3.10.2.

2.3 Neutral Kaon Spectrometer (NKS)

$K^0$'s were measured with NKS by detecting $K_S^0 \rightarrow \pi^+\pi^-$ decay channel. NKS was used as a TAGX spectrometer at the Electron synchrotron of Institute of Nuclear Study,
University of Tokyo (INS-ES)[40] and moved to Tohoku University after the shutdown of INS-ES. Figure 2.5 shows the detector configuration. The target cell was located in the vacuum chamber at the center of spectrometer. Inner hodoscope(IH) surrounded the vacuum chamber and acted as a time 0 counter. Two types of drift chambers, straw drift chamber(SDC) and cylindrical drift chamber(CDC), were located in the magnetic field region for track and momentum analysis. Outer hodoscope(OH) was outside of drift chamber and gave not only the information on time of flight but also the vertical positions of the charged particles. These detectors covered the geometrical acceptance of $\pi$ sr. $K^0$'s were identified by measuring $\pi^+$ and $\pi^-$ in coincidence by left and right detector arms.

Because the $\gamma \rightarrow e^+e^-$ process caused huge backgrounds in trigger level, electron veto counters were set on the middle of OH to reject the charged particles flying on the horizontal plane along beam line.
2.3.1 TAGX Magnet

TAGX magnet was a dipole type magnet with 107 cm diameter and 60 cm gap. The magnetic field was 0.5 Tesla at the maximum with 500 A.
The magnetic field distribution was calculated by TOSCA program. Figure 2.6 shows the distribution of vertical component of the magnetic field. The strength of magnetic field by TOSCA has about 2% systematic error by comparison with the measured values at INS-ES and at LNS.

![Diagram of magnetic field distribution](image)

Figure 2.6: Vertical component of the magnetic field along beam line calculated by TOSCA. The radius of pole pieces are 53.5 cm. Positions of chamber, OH, and parts of magnet are drawn in figure.

### 2.3.2 drift chamber

The tracking device of NKS consists of two types of drift chambers, namely, honeycomb type cylindrical drift chambers and straw type cylindrical drift chambers.

Figure 2.7 shows the structure of these drift chambers. Operation condition is listed in Table 2.2. Due to existence of non uniform electric field, the relation between drift length and drift time (X-T relation) is not linear. The parameters of X-T relation are adjusted for each layer units. The correct parameters are calculated by iteration of tracking and fitting parameter (see Sect.3.4).
Figure 2.7: Structure of drift chamber. The position of sense wires are described.

SDC

SDC is also a set of two chamber, which covers the angular ranges from 10 to 170 degrees and the radial ranges from 7.18 to 10.19 cm. The sense wires are made of gold plated tungsten ($\phi 20 \mu$m), and the straws are made of aluminized mylar film with 180 $\mu$m thickness.

SDC includes 4 layers of sense wires.

CDC

CDC is a set of two honeycomb type drift chambers, which covers the angular ranges from 15 to 165 degrees, and the radial ranges of 13.8 to 48.6 cm.

The geometrical parameters are listed in Table.2.3. The field wires are arranged hexagonally around sense wire (Fig.2.7). Total 12 layers of the sense wires are grouped into 4, and each group has 3 layers. In the present experiment, the 3rd layers of each group were not used. The sense wires are made of gold plated tungsten ($\phi 30 \mu$m) for
2.3. NEUTRAL KAON SPECTROMETER (NKS)

Table 2.2: Operation condition of drift chamber.

<table>
<thead>
<tr>
<th>gas mixture</th>
<th>Ar (50%) + C₂H₆ (50%) at STP</th>
</tr>
</thead>
<tbody>
<tr>
<td>high voltage</td>
<td>3000 V for CDC, 1900 V for SDC (typical value)</td>
</tr>
<tr>
<td>hit information</td>
<td>horizontal only</td>
</tr>
</tbody>
</table>

Table 2.3: The design of SDC and CDC. Cell size is written in cm or degree [square brackets].

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>straw size (cm)</th>
<th>radius of layers (cm)</th>
<th>#wires (sense)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.475</td>
<td>7.18</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>0.535</td>
<td>8.07</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>0.600</td>
<td>9.07</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>0.675</td>
<td>10.19</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>cell size (cm)</th>
<th>radius of layers (cm)</th>
<th>#wires (sense)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.084 [9.0°]</td>
<td>13.8</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>1.249 [9.0°]</td>
<td>15.9</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>1.414 [9.0°]</td>
<td>18.0</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>1.164 [5.4°]</td>
<td>24.7</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>1.263 [5.4°]</td>
<td>26.8</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>1.362 [5.4°]</td>
<td>28.9</td>
<td>28</td>
</tr>
<tr>
<td>11</td>
<td>1.243 [4.0°]</td>
<td>35.6</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>1.316 [4.0°]</td>
<td>37.7</td>
<td>39</td>
</tr>
<tr>
<td>13</td>
<td>1.389 [4.0°]</td>
<td>39.8</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>1.299 [3.2°]</td>
<td>46.5</td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>1.357 [3.2°]</td>
<td>48.6</td>
<td>49</td>
</tr>
<tr>
<td>16</td>
<td>1.416 [3.2°]</td>
<td>50.7</td>
<td>50</td>
</tr>
</tbody>
</table>

inner two layers and stainless steel for 3rd layer in each group. The field wires are made of molybdenum (ϕ100μm).

The inner and outer windows are made of mylar sheet of 200 μm thickness.

After this, we define the consecutive numbers from 1 to 16 as the layer number through SDC and CDC.

2.3.3 Inner hodoscope (IH)

IH is the scintillator hodoscope with 120 mm long and 5 mm thickness, and segmented by 6 pieces at both left and right side as shown Fig.2.8. The scintillation photons are guided to outside of the magnet by optical fiber cable and amplified by 1 inch PMT to avoid the effect of the magnetic field. Because the counting rates were very high, the additional high voltages were provided to last 2 dynodes to avoid the decreasing of the gain.

IH was used not only as time of flight counters but also as a time 0 counters in the trigger. Dynamic range of the energy deposit at IH should be large from 1 MeV for minimum ionizing particle to 10 MeV for proton of low momentum of 200 MeV/c.
For trigger counters, CFD (Constant Fraction Discriminator) were used to prevent time walk from the large difference of pulse height, on the other hands, timing signal discriminated by LED (Leading Edge Discriminator) were sent to TDC for TOF measurement. Time walk was corrected in the offline analysis as described in Sect.3.2.

2.3.4 Outer hodoscope (OH)

OH are scintillation hodoscope, where 2 PMTs are mounted at both ends of each scintillator, segmented by 17 pieces at both left and right side as described in Fig.2.4. The sizes are about 600 mm height, 10 mm thickness, and typically 150 mm width. For the OH in the magnet gap, the scintillation photons are guided to outside of the magnet by fiber cable and amplified by 2 inch PMTs. The PMTs are shielded by isolated iron cylinders to reduce the effect of magnetic field.

The signals of OH are used to make trigger signal. In analysis, the informations of the time of flight are achieved from corrected TDC of IH and OH and the vertical positions of charged particles are evaluated by the time differences of the signal from up- and downside PMTs.

2.3.5 Electron veto counter (EV)

EV are scintillation counters and set to suppress the background from $\gamma \rightarrow e^+e^-$ process in trigger level. They cover vertically \pm 2.5 cm to the horizontal plane involving beam line at OH position. The geometrical acceptance is reduced about 8 \%.
2.3.6 Sweep magnet
To suppress the serious background from the $e^+e^-$ pair creation, a sweep magnet was placed between the radiator and NKS. Furthermore, helium bag occupied from the sweep magnet to front of the target. Besides, to remove the beam halo, a collimator was arranged just in front of the sweep magnet. The collimator is made from lead, and its hole is diameter of 1.0 cm and length of 30 cm. Although the materials in upstream are less than those at target, $e^+e^-$ generated at upstream meets the trigger condition easily. Hence, the materials in upstream had to be as small as possible so as to suppress the background in trigger level. On the other hand, $e^+e^-$ generated at target caused the large single rates on each detectors. Thus, the conditions of the trigger rate and operation of the detectors, especially drift chambers, limited the beam intensity.

2.4 Target system
we used a liquid deuterium target in order to investigate the elementary process of the photo-production of neutral kaon on a neutron.

The target system which is able to control the liquefaction of the deuterium and kept the liquid state were adapted to NKS. The target system was designed with attention to maximizing the yield of $K^0$, minimizing the background and safety of operation. For the $K^0$, target thickness was optimized and density of the liquid deuterium was kept as high as possible. For the background, the amount of material around the target had to be reduced. Concerning safety operation, the system was controlled remotely by LabVIEW program running on a Linux machine in the experimental hall, and we could operate and monitor it from counting room via network.

The temperature around a liquid target and the pressure of the residual gas were monitored all through the period of experiment, and the density of the target was estimated with small statistic and systematic error.

2.4.1 Design of target system
The outline figure of target system is shown at Fig. 2.9. Although the target cell was placed at center of NKS, the refrigerator should be placed outside of the magnet because the space around target was quite limited. The long cylindrical part of the cryostat was inserted in the vertical hole with an inner diameter of 120 mm at the center of the yoke and pole. At the top of the cryostat, 2-Stage Gifford-McMahon refrigerator (Sumitomo Heavy Industry RD-208B) was placed. The ultimate temperature of the first and second stage were measured as 9.2 K and 38.1 K, respectively, in the manufacturer’s examination. Figure.2.10 shows the load map of the capacity of this refrigerator. The cooling powers of two stages were 20 W at 50 K and 8 W at 20 K, respectively. At the second stage of the refrigerator, an oxygen-free copper rod was attached to extend its stage to the center of NKS. Two heat exchangers, condenser and re-condenser, were located at the end of the copper rod. The deuterium was liquefied at the condenser and then dropped into the target cell. The re-condenser worked to liquefy the evaporated deuterium from the cell. The refrigeration power of the first stage was also used to cool
the thermal shield made of aluminum alloy. The heat transfer to the radiation shield was estimated to be 3.7 W in the condition that the surrounding temperature was 300 K, temperature of the shield was 50 K, and the vacuum of the cryostat was $1.8 \times 10^{-3}$ Pa. The heat transfer to the copper rod was 0.6 W when the temperature of the rod was 18 K in the above condition.

![Figure 2.9: Schematic view of the target system.](image)

### 2.4.2 target cell

The cell in which the liquid deuterium is accumulated is shown Fig.2.11. The holder is made of aluminum with 1mm thickness and the windows on the beam line are mylar film with 75μm thickness in order to reduce the background from $e^+e^-$ pair creation and the effect of the multiple scattering of charged particle.

The inside diameter of open parts of the target cell are 40 mm, which is decided from beam size of about 5 mm in $\sigma$ and that the fluctuation of position of the beam spot is less than 5 mm.

When the cell is filled by the liquid deuterium, the mylar windows expanded due to the pressure. Its effect is estimated from the data analysis and calculation by finite element method, and achieved about 1 mm expansion for both windows. Therefore the target width is evaluated 34 mm $\pm$ 2 mm along the beam line.
2.4. TARGET SYSTEM

Figure 2.10: Schematic view of the target system.

Figure 2.11: The picture of target cell.

2.4.3 Equipment

A 50 W heater and a temperature sensor were placed on the copper rod. The temperature was controlled by feeding back the measurement of sensor to heater. Two more
temperature sensors were placed to measure the temperature of the gas or the liquid directly. One sensor was placed in the pipe between the re-condenser and the target cell. The other one was placed in the cell. These kind of temperature sensors have low sensitivity to the magnetic field and high resistance to ionizing radiations.

The temperature of liquid deuterium was about 19 K and changed within ± 0.1K. The pressure of the residual gas was near 50 kPa and changed within ± 2 kPa. The density of the liquid deuterium target is evaluated from the temperature and pressure by rule of thumb(Appendix A). The density is estimated 0.17 g/cm$^3$ typically (Sect.3.10.3).

### 2.5 Data acquisition system

#### 2.5.1 setup

The counting house was located on the ground far from the experimental hall, therefore signals from detectors were sent through 50~70 m cables except for the discriminated signals from drift chambers and tagger. Analog signals were sent by RG58/U except for ones from IH which were sent by RG8/U. Attenuation of the signal height through these cables were typically 70% or 80%.

The signals of IH, OH and EV were digitized in counting house to be used to make triggers and sent to TDC. For IH, the signal was divided before digitization and the mate was sent to ADC. For OH and EV, the signals were divided at PMT in experimental hall and the mate were sent to ADC through 100 m long cable.

On the other hand, tagger signals were digitized in experimental hall and taken a co-incidence between TagF and TagB. We could change the mode whether the coincidence
was taken by relay switch from the counting house. Fig.2.15 shows the tagger trigger logic. Thus, the logic signal of TagF was sent to TDC in counting house, in contrast, logic and raw signal of TagB were sent to TDC and ADC, respectively. Besides, in order to count the number of photons, the logic signals of TagF, TagB and SUM were sent to CAMAC scaler. Scaler data were read at end of each spill.

The signal of drift chamber was amplified by pre-amp on chamber and digitized by amp-discriminator in experimental hall. Section 2.5.3 mentions as for chamber read out system.

Figure 2.13 shows a diagram of the data acquisition system. The system operated synchronously to the accelerator cycle. The data for IH, OH, EV and tagger were fed into the TDC and ADC modules of the TKO or CAMAC. The data in TKO were then stored in VME memory module (SMP). The SMP had dual memory and exchanged the roles of storing and reading event by event to take data efficiently.

![Data acquisition system diagram](image)

Figure 2.13: Data acquisition system.

### 2.5.2 Trigger logic

The trigger conditions of this experiment are shown in Table 2.4, and trigger logic is shown in Fig.2.14.

The main trigger (MT) logic was generated of 3 parts.

\[ MT = LEFT \otimes TIGHT \otimes BEAM \]

**BEAM**: The trigger for that the photon was generated in the energy region of 0.8 to 1.1 GeV and generated charged particles.
**LEFT or RIGHT:** Left or Right trigger corresponding to that more than one charged particles passed through IH, DC and OH.

To reject the $e^+e^-$ background events, electron veto countors were required at both Left and Right trigger.

<table>
<thead>
<tr>
<th>Main Trigger</th>
<th>MT = LEFT $\otimes$ RIGHT $\otimes$ Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Trigger</td>
<td>LEFT = IHL $\otimes$ OHLU $\otimes$ OHLD $\otimes$ EVL</td>
</tr>
<tr>
<td>Right Trigger</td>
<td>RIGHT = IHR $\otimes$ OHRU $\otimes$ OHRD $\otimes$ EVR</td>
</tr>
<tr>
<td>Beam Trigger</td>
<td>BEAM = (IHL$\otimes$IHR$\otimes$SUM)</td>
</tr>
<tr>
<td>Tagger (B: Backup Counter)</td>
<td>TagB = TagB1 $\oplus$ $\cdots$ $\oplus$ TagB12</td>
</tr>
<tr>
<td>(F: Finger Counter)</td>
<td>SUM1 = TagB1 $\otimes$ (TagF1 $\oplus$ $\cdots$ $\oplus$ TagF4)</td>
</tr>
<tr>
<td></td>
<td>SUM = SUM1 $\oplus$ $\cdots$ $\oplus$ SUM12</td>
</tr>
<tr>
<td>Left Side (U: up, D: down)</td>
<td>IHL = IHL1 $\oplus$ $\cdots$ $\oplus$ IHL6</td>
</tr>
<tr>
<td></td>
<td>OHLU = OHLU1 $\oplus$ $\cdots$ $\oplus$ OHLU17</td>
</tr>
<tr>
<td></td>
<td>OHLD = OHLD1 $\oplus$ $\cdots$ $\oplus$ OHLD17</td>
</tr>
<tr>
<td></td>
<td>EVL = EVLF $\oplus$ EVLB</td>
</tr>
<tr>
<td>Right Side</td>
<td>IHR = IHR1 $\oplus$ $\cdots$ $\oplus$ IHR6</td>
</tr>
<tr>
<td></td>
<td>OHRU = OHRU1 $\oplus$ $\cdots$ $\oplus$ OHRU17</td>
</tr>
<tr>
<td></td>
<td>OHRD = OHRD1 $\oplus$ $\cdots$ $\oplus$ OHRD17</td>
</tr>
<tr>
<td></td>
<td>EVR = EVRF $\oplus$ EVRB</td>
</tr>
</tbody>
</table>

Table 2.4: Trigger conditions.

For tagger calibration run, only tagger trigger was used as main trigger. This trigger was not biased by conditions of NKS side.

not yet written

### 2.6 Data summary

The experiments were carried out at September, November, December in 2003 and April, May, June in 2004. Each periods was about 2 or 3 weeks. The duty factor was about 60 % with 20 second of flat top time as shown in Fig.2.3. The radiator was inserted for 18 second.

The intensity of beam was from 2 to 3 MHz in the region from 0.8 to 1.1 GeV photon energy.

Table
Figure 2.14: Schematic view of trigger logic.

Figure 2.15: Schematic view of trigger logic for tagger. The output signals are sent to TDC and scaler.
### Table 2.5: Data summary of normal data taking for each experimental period.

<table>
<thead>
<tr>
<th>period</th>
<th>target</th>
<th>#spill</th>
<th>#photon</th>
<th>typical intensity (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>liq. $D_2$</td>
<td>9.7E3</td>
<td>5.6E11</td>
<td>1.5</td>
</tr>
<tr>
<td>September  2nd</td>
<td>empty target</td>
<td>2.1E3</td>
<td>7.5E10</td>
<td>1.7</td>
</tr>
<tr>
<td>3rd</td>
<td>liq. $D_2$</td>
<td>6.3E3</td>
<td>3.2E11</td>
<td>2.6</td>
</tr>
<tr>
<td>November</td>
<td>liq. $D_2$</td>
<td>2.7E4</td>
<td>8.5E11</td>
<td>1.7</td>
</tr>
<tr>
<td>December</td>
<td>liq. $D_2$</td>
<td>1.6E4</td>
<td>5.4E11</td>
<td>1.8</td>
</tr>
<tr>
<td>April</td>
<td>liq. $D_2$</td>
<td>1.9E4</td>
<td>7.4E11</td>
<td>2.2</td>
</tr>
<tr>
<td>May</td>
<td>liq. $D_2$</td>
<td>3.9E4</td>
<td>1.6E12</td>
<td>2.3</td>
</tr>
<tr>
<td>June</td>
<td>liq. $H_2$</td>
<td>2.9E4</td>
<td>1.2E12</td>
<td>2.3</td>
</tr>
</tbody>
</table>

### Table 2.6: Data summary of tagger trigger run.

<table>
<thead>
<tr>
<th>period</th>
<th>run name</th>
<th>#photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>November</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>December</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3

Analysis

3.1 Outline

The goal of the analysis in the present experiment is to obtain the differential cross section of $K^0$ photo production and compare with theoretical calculations. In this chapter, those procedures are described.

We measured events in which at least two charged particles were detected by NKS. The invariant mass of $K^0$ is calculated as following formula,

$$M(\pi^+\pi^-)^2 = \left(\sqrt{\vec{p}_{\pi^+}^2 + m_{\pi^+}^2} + \sqrt{\vec{p}_{\pi^-}^2 + m_{\pi^-}^2}\right)^2 - (\vec{p}_{\pi^+} + \vec{p}_{\pi^-})^2,$$

where $\vec{p}$ is a 3-momentum and $m_\pi$ is a mass of pion $\pi$ respectively.

The momentum of the charged particles is calculated from the curvature of tracks, and the particle velocities are calculated from the length of the tracks and time of flight between IH and OH.

In sect.3.2, the way of calibration for hodoscope, IH,OH and tagger counters are explained, and performances of hodoscope are shown.

Calibration and performance of drift chambers are shown in sect.3.4 and 3.5. Simultaneously, tracking method and momentum reconstruction are explained. The ways to suppress the background are explained in sect.3.6, 3.7 and 3.8. Evaluating various efficiencies and calculating the cross sections are described in sect.3.10.

3.2 Calibration of hodoscope

For IH, OH and TagB, which have ADC data, the time measured by TDC were corrected by throwing correction.

$$T_{cor} = T_{raw} - \frac{p_0}{Q - p_1} + p_2$$

where $Q, T_{raw}$ are ADC and TDC data of a hodoscope, $p_0, p_1, p_2$ are fitting parameters, $T_{cor}$ is corrected time, respectively. Although IH were used as time 0 counter in trigger level, relative difference of timing among IH existed within 1 nsec. Therefore,
time difference between each IH and each tagger are adjusted to be 0 run by run in analysis. Figure 3.1 shows the time difference distribution between IH and TagF when the multiplicity of TagF is 1. Details of analysis for tagger are described in Sect. 3.3.

The peak at 0 is true coincidence, and others with 2 nsec cycle are accidental coincidence which is caused by beam bunch. The time resolution is derived to 420 psec in $\sigma$.

Figure 3.1: Time difference between IH and tagger. The beam bunch structure of 2 nsec can be seen. The time resolution was derived to 420 psec in RMS.

Figure 3.2 shows the time difference between IHL and IHR when the particles tracks can be reconstructed and are identified as pions (see Sect. 3.6). Fitting by the gaussian, the time resolution is estimated about 660 psec in $\sigma$.

Figure 3.2: Time difference between IHL and IHR. The time resolution was derived to 660 psec in RMS.

We required the time gates for these time difference distributions, $\pm 1.3$ nsec for IH-tagger and $\pm 2.0$ nsec for IHL-IHR, respectively. The width of these gates are corresponding to about 3 $\sigma$. 
In the case of OH, the time difference between up and down gives the information of the vertical position of the track, namely,

$$Z_{OH} = v \cdot (T_{down} - T_{up})/2,$$

where $T_{up}$ and $T_{down}$ are corrected times at up and down PMT, $v$ is the propagation velocity of the scintillation light.

Figure 3.3 shows the vertical distribution at OHR1 when pions are selected. The dent at $z=0$ is due to EV. The length of OH is 60 cm, and the width of EV is 5 cm.

![Figure 3.3: Distribution of vertical position at OHR1 calculated from time difference between up and down PMT signals for pions.](image)

Moreover, time of flight (TOF) is derived from the time difference the mean time for up and down of OH to IH. The offset of mean time of OH are adjusted using the trajectory informations of the particles to give TOF correctly.

### 3.3 Calibration of tagger

#### 3.3.1 Clustering and timing gate

Tagger gives us the informations of the photon energy and the number of photons. In this section, the way how the accidental hits are removed and the clusters are decided is explained.
Figure 3.4: *The resolution of the time of flight.*

Figure 3.5 shows the hit pattern of TagF. The structures around TagF15 and TagF45 come from support frames of the window of vacuum chamber of STB-ring, where some parts of electrons lose its energy and are scattered. This effects were well reproduced and understood by Geant4 simulation.

![Figure 3.5: Tagger hit pattern from the number of TDC hits.](image)

Figure 3.6 shows the time difference between TagF and TagB. Because the pulse height correction is applied only to TagB as mentioned in Sect.3.2, the shape of the time difference is not symmetric. However, the time gate of $|\text{time diff}| < 2\ \text{nsec}$ was applied because the effect of the tail was small.

Next, relative timings among each TagF segments were adjusted using time difference between IH and Tagger and gated to remove the accidental hits as mentioned in Sect.3.2.

Finally, TagF hits were collected in clusters. The cluster was obtained from TagF hits in the same timing and serial segments in coincidence with TagB. This cluster is defined as TagH, and its segment number and time were the average of associated TagF hits. Figure 3.7 shows the time difference between TagH in a trigger, in which the condition of $\#\text{hit}$ of TagH is 2. The lower figure represents the correlation between
accidental events, and TagF has the resolution of $530/\sqrt{2} \sim 370$ psec. The resolution in the upper figure is slightly larger than that in the lower figure. This was caused by accidental hit at TagB.

Then, the time gate of $|\text{time diff}| < 1.8$ nsec was applied.

---

![Figure 3.6](image1.png)

**Figure 3.6:** Time difference between TagF and TagB. The multiplicity of TagF is required to be 1.

![Figure 3.7](image2.png)

**Figure 3.7:** Time difference between TagH and TagH with $\#\text{TagH}=2$. The lower figure is required that the difference of TagB segments of clusters is more than 2.
3.3.2 Energy calibration

In this section, the relation between TagF segment and photon energy. The energy of photon was calibrated at July 2004 [39]. Figure 3.8 shows the result. The accuracy of energy was measured to be ± 10 MeV.

However, at the experiment using liquid D2, tagger hit pattern was shifted by 1 segment to low energy side (Fig.3.9). This causes the systematic error of −6 MeV.

![Figure 3.8: Result of the photon energy calibration. The energy was calibrated via $\gamma \rightarrow e^+e^-$ conversion with 4 magnetic fields of spectrometer, in order to measure all range of the tagged photon energy.](image1)

![Figure 3.9: Difference of hit pattern TagF. The structures around segment 15 and 30 were changed.](image2)

3.4 Calibration of drift chamber

The drift chambers play an essential role in this experiment because the momentum of charged particles is obtained from the trajectory in the magnetic field. Furthermore, the vertex point of $K^0$ decay is reconstructed by extrapolating from trajectories of 2 pions.

Due to non uniformity of the electric field in drift space, the relation of a drift length and a drift time (X-T relation) is not linear. We assume that X-T relation is polynomial
expression, 7th order for CDC and 4th order for SDC. The X-T relations are adjusted run by run. The parameters are decided for each layers. Fig.3.10 shows X-T relation for two layers in SDC and CDC respectively at a certain run.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig310.png}
\caption{x-t relation of SDC layer 2 (left) and CDC layer 14 (right)}
\end{figure}

3.5 Tracking

3.5.1 Pre-selection before tracking

The procedure of pre-selections before tracking is presented in this section. First, a selection by maximum number of hits in each layer (MLH) was applied. Figure.3.11 shows MLH distribution for Layer 1 and 14 in both sides.

Events with large MLH were almost caused by electromagnetic background processes and take large time for searching tracks due to a large number of combinations of hits. Therefore, those events were rejected to work analysis efficiently. In present analysis, the threshold was 10.

Next, clusters were made of good hits corrections in the following groups,

- SDC (Layer\#1-\#4),
- CDC1 (Layer\#5 and \#6),
- CDC2 (Layer\#8 and \#9),
- CDC3 (Layer\#11 and \#12),
- CDC4 (Layer\#14 and \#15).

The cluster combined with neighboring hits between layers, e.g., (layer\# - wire\#)=(1-10,2-9,3-10,4-11) in SDC group.

Therefore, the track candidates were made of the clusters in each group under following condition,
• 1 cluster in each group,
• 4 groups at least,
• 6 hits at least in total,
• the selection of the angles between clusters
  \[ |\phi_{CDC1} - \phi_{SDC} | < 30^\circ \]
  \[ |\phi_{CDC2} - \phi_{CDC1} | < 15^\circ \]
  \[ |\phi_{CDC3} - \phi_{CDC2} | < 15^\circ \]
  \[ |\phi_{CDC4} - \phi_{CDC3} | < 15^\circ \]

where \( \phi \) is the angle in the horizontal plane against the beam direction.

### 3.5.2 Tracking of particle trajectory

The trajectory of a charged particle in the magnetic field was calculated by the cubic spline interpolation method\[41\]. Because the vertical positions in drift chamber were not measured, fitting was carried out in mid-plane using vertical component of magnetic field at wire positions by least \( \chi^2 \) method, firstly. The bad track (\( \chi^2 > 300 \)) was rejected. After OH corresponding to the track was found, vertical components of magnetic field off mid-plane were used in re-fitting assuming a trajectory connecting from origin point to vertical position at OH, in which horizontal positions on a track were known by previous fitting. In latter analysis, robust fitting method by J.W.Tukey\[42\] was used, which was a method to find a plausible track in consideration of weights for hits. The
weights were changed by the residual calculated in previous fitting. In these fitting, momentum of track was parameterized and defined from the tracking result.

The trajectory was extrapolated from DC to OH by 4th Runge-Kutta method, in which initial conditions were position and the derivative at outermost layer and momentum from fitting. In Runge-Kutta method, secondary derivative at each step was calculated using vertical component of magnetic field and initial momentum. The momentum was assumed not to be changed. Thus, the nearest OH were searched and labeled to the track. The IH corresponding to the track was searched by simply extension of a track. Figure 3.12 shows the residual distribution between a center of IH or OH and a point extrapolated from the track. The typical width of IH and OH are 2.7 cm and 15 cm respectively (see sect.2.3.3, 2.3.4). The cuts for these distribution are 1.6 cm and 10.0 cm respectively.

![Figure 3.12: The residual distribution between a center of hodoscope and a point extrapolated from track.](image)

**3.5.3 Momentum reconstruction**

Particle momentum \( p \) was calculated by

\[
p = \sqrt{p_H^2 + p_V^2},
\]

where \( p_H \) and \( p_V \) were horizontal and vertical momenta, respectively. \( p_H \) was calculated from the curvature of the trajectory measured by drift chambers. On the other hand, \( p_V \) was estimated from \( p_H \), \( Z_{OH} \) and flight length (\( fl \)),

\[
p_V = p_H \cdot \frac{Z_{OH}}{fl}.
\]
was the length from IH to OH calculated by 4th Runge-Kutta method from DC to IH and OH.

### 3.5.4 Plane efficiencies and residual resolutions in a plane

Chamber plane efficiency and resolution are estimated for pions (figure 3.13). In these estimation, tracking is carried out except the layer for investigation. To select the events as clear as possible, following conditions are required.

- number of hits in IH, OH, tagger is 1
- max layer hits of DC = 1
- number of tracks is 1 for both Left and Right arms
- hits for both inside and outside of the measured layers (except layer 1,15)
- hits for 2 inside layers for layer 1,15
- pions are selected from relation between momentum and velocity (see Sect.3.6)

Efficiencies are typically 95% for CDC and 90% for SDC.

These resolutions include resolutions of trajectories. Therefore, to estimate the effects of tracking resolution, simulation data are analyzed assuming some resolutions (Fig.3.14). Figure 3.15 shows the ratio of resolutions of between plane and trajectory which are estimated by

\[
\sigma_{\text{calc.}}^2 = \sigma_{\text{assume}}^2 + \sigma_{\text{traj.}}^2
\]

\[
f = \frac{\sigma_{\text{traj.}}}{\sigma_{\text{assume}}} = \sqrt{\frac{\sigma_{\text{calc.}}^2 - \sigma_{\text{assume}}^2}{\sigma_{\text{assume}}^2}}
\]

for each layer

where \(\sigma_{\text{calc.}}\) is derived by fitting the residual distribution, \(\sigma_{\text{assume}}\) is the value introduced to simulation data taking account to the resolution and \(\sigma_{\text{traj.}}\) is the resolution of trajectory. In the range from 300 to 600 \(\mu\)m, the ratios are constant for each layers.

Therefore, using these ratios, the resolutions of data are estimated as

\[
\sigma_{\text{measured}}^2 = \sigma_{\text{plane}}^2 + \sigma_{\text{traj.}}^2 = (1 + f^2)\sigma_{\text{plane}}^2
\]

\[
\sigma_{\text{plane}} = \frac{1}{\sqrt{1 + f^2}}\sigma_{\text{measured}}
\]

where \(\sigma_{\text{measured}}\) is derived by fitting the residual distribution, \(\sigma_{\text{plane}}\) is the correct resolution of each plane and \(\sigma_{\text{traj.}}\) is the resolution of trajectory whose relation to \(\sigma_{\text{plane}}\) is assumed to be the same with that of simulation. Figure 3.16 shows results after subtraction of resolution of trajectories. Typical value of resolutions are 400\(\mu\)m for CDC and 500\(\mu\)m for SDC.

Figure 3.17 shows \(\chi^2\) distribution for events selected pions assuming the position resolution of 300 \(\mu\)m for each layers. For detecting \(K^0\), we apply the cut of \(\chi^2 < 8\) for 2 tracks.
3.6 Particle Identification

The process $\gamma \rightarrow e^+e^-$ was the most largest background. In analysis, $e^+e^-$ generated upstream were removed by vertex point selection. Figure.3.18 shows vertex point distribution along the beam line. The structures in upstream are corresponding to the step size of Runge-Kutta method used to extrapolation of trajectory. When opening angle is very small and curvature is small, vertex point tends to be calculated at extrapolated point on the trajectory. Because the acceptance for $e^+e^-$ events generated near the target is much smaller than that generated in upstream, most of $e^+e^-$ events are removed by selection of the vertex point. Furthermore, the opening angle of $e^+e^-$ is very small, $\cos \theta \sim 1$, on the other hand, the opening angle of $\pi^+\pi^-$ from $K_S^0$ is relatively large.

Figure.3.20 shows the opening angle distribution for $K_S^0$ by simulation (conditions of simulation are explained in Sect.3.8.2). The opening angle for $K_S^0$ is less than 0.8, kinematically. Applying the cut of $\cos \theta < 0.8$, almost all $e^+e^-$ events can be removed. We apply the opening angle cut, $-0.9 < \cos \theta < 0.8$.

Figure.3.21 shows the scatter plot of beta inverse v.s. momentum of particles after applying cuts of opening angle and vertex point, $-0.9 < \cos \theta < 0.8$, $V_x > -3$ [cm]. The sign of momentum represents the charge of a particle. The type of particles is identified by selecting the regions drawn by solid lines. These regions are represented as following formula,

$$
\begin{align*}
0.5 < 1/\beta \\
\pm 0.144/(1/\beta - 0.2) - 0.08 \lesssim p \lesssim \pm 0.5/\sqrt{1/\beta^2 - 1}
\end{align*}
$$

for $\pi^\pm$, 

Figure 3.13: Plane efficiencies and residual resolutions for each planes.
Figure 3.14: Chamber resolutions evaluated by analysis for simulation data. Resolutions are assumed as 300, 420, 500, 600 μm, respectively.

Figure 3.15: Estimation of the ratios resolution for trajectories to that for plane for each layers. Resolutions are assumed as 300, 420, 500, 600 μm, respectively.

Figure 3.16: Chamber resolutions for each layers before (top) and after (bottom) subtraction of resolutions of trajectories.
3.7 Event selection

When two trajectories are obtained, a vertex point can be reconstructed as an intersection point of extrapolations of these trajectories. Figure 3.22 shows the method of vertex reconstruction. We applied a cut to the distance of two tracks, \( \text{dist} < 0.0001 \text{cm} \)

\[
0.5/\sqrt{1/\beta^2 - 1} < p < 2.5/\sqrt{1/\beta^2 - 1} \quad \text{for proton.}
\]
Figure 3.19: Upper panel shows vertex point distribution along the beam line. Lower panel shows the differential of vertex point distribution and results of the fitting with two gaussians. Vertex point resolution is estimated about 1.3 mm.

Figure 3.20: Opening angle distribution for $\pi^+\pi^-$ from $K^0_S$ estimated by simulation.

(Fig.3.23).
Figure 3.24 shows the vertex point distribution around the target for $\pi^+\pi^-$ events. Figure 3.25 shows the distribution along the beam line. The materials around the target are drawn in the figure. Although most of the events come from the target, the events
Figure 3.21: The scatter plot of beta inverse v.s. momentum. The sign of momentum represent the charge. To remove the electrons and positrons, the events are required that a vertex can be reconstructed from two tracks and its opening angle, $\theta_{OA}$, is $\cos \theta_{OA} < 0.8$.

null

Figure 3.22: Distance between two tracks.

which were generated at the vacuum chamber or mylar film can be seen. Figure.3.26 show invariant mass spectra for the events reconstructed the vertex points in the target region and the decay volume. For events in the target region, huge background of non-strangeness process, e.g. $\rho$, nucleon resonances, multi pion production, etc, exist,
thereby $K^0$ events are not seen in the invariant mass spectrum. In contrast, selecting events reconstructed vertex out of the target, a peak of $K^0$ can be clearly seen because the lifetime of $K^0$, $\tau \sim 2.68$ cm, is relatively longer than that of other processes which decay immediately. Thus, we define the Decay Volume for searching $K_s^0$ as following formula,

$$
( V_{T_x} > 2.0 \text{ (cm}) \oplus ( |V_{T_y}| > 2.5 \text{ (cm}) ) \\
\times \quad r = \sqrt{(V_{T_x} - 2.0)^2 + V_{T_y}^2} < 5.0 \text{ (cm),}
$$

where $V_{T_x}$ and $V_{T_y}$ are the coordinates in the frame in which the center of the target is origin. Because the target position was different each experimental period, the coordinates of $V_{T_x}$ and $V_{T_y}$ are used.

Besides, suppressing the background, the generating points of $K^0$ are calculated so as to select events generating in the target. The cut conditions are

$$
1.8 < dlen < 5.5 \text{ (cm)} \\
|G_x| < 1.8, \quad |G_y| < 2.5,
$$

where $G_x$ and $G_y$ are generating points measured from the center of target, and $dlen$ is the distance between generating point and the vertex point as shown in Fig.3.27. $dlen$ and $G_x, G_y$ were derived as following formula,

$$
\begin{align*}
\text{dlen} &= \frac{\vec{P}_K \cdot \vec{V}_T}{\vec{P}_K} \\
\vec{G} &= \vec{V}_T - \text{dlen} \cdot \frac{\vec{P}_K}{\vec{P}_K}
\end{align*}
$$
3.8 Estimation of the background

In Fig. 3.26, the backgrounds exist in the $\pi^+\pi^-$ invariant mass spectrum even for decay volume, and the ratio of signal(S) to noise(N), S/N, is about 1 in the mass gate from 0.46 to 0.54 GeV/c$^2$. The origin of these background are considered as

**case 1** leakage from the target region due to the finite resolution of the vertex points.

---

Figure 3.24: The vertex distribution. The materials around target are drawn. Almost all events come from target region.

Figure 3.25: The vertex distribution along beam line after selecting $\pi^+\pi^-$ events.
Figure 3.26: $\pi^+\pi^-$ invariant mass spectrum in the target region (up) and in the decay volume (down).

Figure 3.27: Schematic view of the calculation of generate points.

case 2 wrong combination, such as $\pi^+$ from $K^0$ and $\pi^-$ from $\Lambda$. 
3.8.1 case 1

The background of case 1 is estimated from the experimental data whose vertex points are reconstructed in the target region, because it is considered that the kinematics of this background are almost the same with those of events from target region.

3.8.2 case 2

The background of case 2 is estimated by Geant4 simulation. In the simulation, the following conditions were assumed,

- $K^0$ and $\Lambda$ were generated to be isotropic in CM frame,
- the cross section increased linearly with the energy of photon,
- Hulthen wave function was used as the Fermi momentum distribution of a neutron.

Figure 3.28 shows the invariant mass spectrum for $\pi^+\pi^-$ from simulation data. The shapes of momentum and angular distributions for the wrong combination events were also evaluated. If the assumptions of this evaluation are changed, these shapes may be also changed. Fig.3.29 shows the results for some situations of the angular and photon energy dependences, and Table 3.1 lists the conditions of these situations. These ambiguities cause the systematic error on the shape of the B.G case 2 of typically $\pm 5\%$.

![Invariant mass spectrum from simulation](image)

Figure 3.28: Invariant mass spectrum from simulation. The contamination of the combination of $\pi^+$ from $K^0$ and $\pi^-$ from $\Lambda$ are shown (dotted line), $\pi^+\pi^-$ from $K^0$ (dashed line).

Then, invariant mass from data (Fig.3.26) are fitted using a gaussian for the peak of $K^0$ and the shapes of two backgrounds which are only scaled in the three photon energy regions, that is $0.8 < E_\gamma < 0.9, 0.9 < E_\gamma < 1.0$ and $1.0 < E_\gamma < 1.1$ (Fig.3.30).
Figure 3.29: The momentum shape of wrong combination events for some conditions of simulations. The conditions for each case are listed in Table 3.1. Case f is the condition evaluating the momentum and angular shape used present analysis.

Table 3.1: The list of conditions of simulations evaluating the shape of momentum and angular distribution. Case f is the condition evaluating the momentum and angular shape used present analysis.

<table>
<thead>
<tr>
<th>Case</th>
<th>Fermi momentum</th>
<th>energy dependence</th>
<th>angular distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Hulthen w.f.</td>
<td>Linear from threshold</td>
<td>Kaon-MAID</td>
</tr>
<tr>
<td>b</td>
<td>Hulthen w.f.</td>
<td>Linear from threshold</td>
<td>SLA</td>
</tr>
<tr>
<td>c</td>
<td>Hulthen w.f.</td>
<td>flat</td>
<td>isotropic</td>
</tr>
<tr>
<td>d</td>
<td>Hulthen w.f.(200 MeV peak)</td>
<td>flat</td>
<td>isotropic</td>
</tr>
<tr>
<td>e</td>
<td>Rest</td>
<td>flat</td>
<td>isotropic</td>
</tr>
<tr>
<td>f</td>
<td>Hulthen w.f.</td>
<td>Linear from threshold</td>
<td>isotropic</td>
</tr>
</tbody>
</table>

### 3.9 Invariant mass selection

We obtained the $\pi^+\pi^-$ invariant mass spectrum in Fig.?? . The RMS of the peak around 0.5 GeV/c$^2$ is less than 14 MeV/c$^2$, which changes as selection of photon energy range. Then, we set the mass gate from 0.46 to 0.54 GeV/c$^2$ to select $K^0$ events. Although the gate corresponds to the width of 3 $\sigma$ of the peak, the inefficiency of $K^0$ selection is larger than 0.3 % due to the tail from analysis resolution. According to the simulation, this inefficiency is less than 4 %.
3.10 Differential cross section

The differential cross section is estimated by

\[
\frac{d\sigma}{d\Omega dp} = \frac{N_{\text{yield}}(p, \theta)}{N'_{\gamma} \cdot N_{\text{target}} \cdot \epsilon_{\text{acpt}} \cdot \epsilon_{\text{DAQ}} \cdot \epsilon_{\text{track}} \cdot \epsilon_{\text{Gate}} \cdot 2\pi \cdot d \cos \theta \cdot dp}
\]

where \( N_{\text{yield}} \), \( N'_{\gamma} \) and \( N_{\text{target}} \) is number of selected events, photons bombarded on the target and targets, \( \epsilon_{\text{acpt}} \) is acceptance of NKS, \( \epsilon_{\text{track}} \), \( \epsilon_{\text{Gate}} \) and \( \epsilon_{\text{DAQ}} \) are efficiency of the tracking analysis, the gating for spectrum and the data taking.

The tracking analysis efficiency is reduced as

\[
\epsilon_{\text{track}} = \epsilon_{\text{MLH}} \cdot \epsilon_{\text{tracking}} \cdot \epsilon_{\text{goodtrack}}
\]

where \( \epsilon_{\text{MLH}}, \epsilon_{\text{tracking}} \) and \( \epsilon_{\text{goodtrack}} \) are cut efficiency of max layer hit selection, track finding efficiency and good track selection efficiency , respectively. Estimation of each efficiency are described in Sect.3.10.4.

The efficiency of gating for spectrum is reduced as

\[
\epsilon_{\text{Gate}} = \epsilon_{\text{GateDiff}} \cdot \epsilon_{\text{GateIM}}
\]

where \( \epsilon_{\text{GateDiff}} \) is efficiency of gating for the time difference between IHL and IHR or between TagF and IH, \( \epsilon_{\text{GateIM}} \) is efficiency of gating for invariant mass spectrum. \( \epsilon_{\text{GateIM}} \) is from 96 to 99.7 % discussed in Sect.3.9. The time gate for the time difference

Figure 3.30: Fitting results of invariant mass spectra. The peak around 0.4 GeV/c\(^2\) come from the wrong combination background and around 0.6 GeV/c\(^2\) comes from the leakage of target events.
between IHL and IHR or TagF and IH is decided to be more than 3σ. Therefore, 
\( \epsilon_{\text{GateTdiff}} = 0.997 \times 0.997 \) and errors are negligible small.

Number of photon is estimated from scaler counts by correcting as follows

\[
N' = f_{\text{att.}} \cdot \epsilon_{\text{tagging}} \cdot \epsilon_{\text{tagana}} \cdot N_{\gamma}
\]

where \( f_{\text{att}} \), \( \epsilon_{\text{tagging}} \) and \( \epsilon_{\text{tagana}} \) is attenuation factor in the target and between target and calorimeter, tagging efficiency and tagger analysis efficiency, respectively. Estimation of these effect are described in Sect.3.10.2

The yields of \( K^0 \) and two backgrounds are corrected by same procedure, thus, the contributions of backgrounds are subtracted in a unit of cross section.

### 3.10.1 Evaluation of acceptance of NKS

Acceptance of NKS is evaluated by Geant4 simulation program. The geometry of NKS is considered realistically. \( K^0 \) is generated in deuterium target with momentum of 0 to 1.0 GeV/c and \( \cos \theta \) of 0.5 to 1 uniformly in laboratory frame. The generating point is uniform in the target along beam line.
The same trigger condition with the experiment is required, and the data is analyzed by the same program. The chamber resolution of 500 μm is assumed, which value is estimated in Sect.3.5. The plane efficiency of chamber and resolution of hodoscope are also assumed the estimated value from data. The number of generated $K^0$ is 40 million for the geometry of each experimental periods. The result is shown in Fig.3.33. Efficiency is maximum at forward region and the momentum region of about 300 MeV/c.

The acceptance of each period is different due to the precision to setup the detectors and the cryostat. As mentioned in Sect.2.4, the position of the target cell in the vacuum chamber was fixed (Fig.2.12). However, the position of the target cell to the NKS in each experimental period was differently due to the set up precision. The positions of the target cell were derived from data and listed in Table 3.2. Figure 3.34 shows the difference of the acceptance among 3 conditions. Each acceptance is different systematically but consistent within the error. The differences among the acceptance of November, December, April and May are not shown but very small.

Figure 3.35 is the contour plot of the acceptance map. To avoid the low efficiency area, 3 regions are defined as drawn. When the cross sections are calculated, the results at Region 1 are mainly compared with the theoretical calculations.
Figure 3.33: Acceptance map evaluated by Geant4. Width of a bin is 0.02 GeV/c and 0.02 for $\cos \theta$.

Table 3.2: Target position in each experimental period. In september, the values correspond to the condition before and after the empty run (1st and 3rd), respectively.

<table>
<thead>
<tr>
<th>period</th>
<th>position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>1st</td>
</tr>
<tr>
<td></td>
<td>3rd</td>
</tr>
<tr>
<td>November</td>
<td></td>
</tr>
<tr>
<td>December</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td></td>
</tr>
</tbody>
</table>

### 3.10.2 Number of photons on target

Number of photons bombarded on target was estimated from scaler counts of tagger. These tagger signals are coincidence ones between TagF and TagB. The estimation must be included the effect as follows

- Absorption of photons between the radiator and the target, especially at a collimator positioned upstream the sweep magnet,
- double count at neighbor segment,
- analysis cut

First effect is named tagging efficiency ($\epsilon_{\text{tagging}}$), second and third are named tagger analysis efficiency ($\epsilon_{\text{tagana}}$), and last one is defined as attenuation factor ($f_{\text{att.}}$).

**Tagging efficiency**

Tagging efficiency was measured at the beginning and end (or after suspending the measurement due to any trouble) of each experimental periods in order to estimate the
3.10. DIFFERENTIAL CROSS SECTION

Figure 3.34: Difference of acceptances among the data-taking periods. The regions of the angle $\theta$ are $0.8 < \cos \theta < 0.9$ to the left figures and $0.9 < \cos \theta < 1.0$ to the right figures. Two conditions at September and one at April are compared in upper figures. In lower figure, the differences between September and April are displayed.

Figure 3.35: Contour plot of acceptance map evaluated by Geant4. Solid lines shows accepted region which have efficiency not too small.

number of photon irradiated the target.

Tagging Efficiency is defined by

$$\epsilon_{\text{tagging}} = f_{\text{att}} \cdot \frac{N_{\text{calorimeter}}}{N_{\text{tagger}}}$$

where $N_{\text{calorimeter}}$ and $N_{\text{TagF}}$ are number of photons injected a calorimeter and tagged with STB-tagger, respectively, and $f_{\text{att}}$ is the attenuation factor between the target and calorimeter. At September 2003, we measured tagging efficiency by the CsI scintillation
Figure 3.36: Angular distribution of events applied invariant mass cut and selected the acceptance region in the photon energy region from 0.9 to 1.0 GeV (upper) and from 1.0 to 1.1 GeV (lower). The background contributions (open triangle for leakage from target, diamond for wrong combination) are compared with data (open square).

counter as calorimeter. It was positioned at 260 cm downstream from the experimental target position. (see Fig.3.38). We used the CsI and lead glass cerenkov counter (LG) at November 2003, and used only LG since December 2003. The position of the lead glass was the same as CsI. Figure 3.39 shows the correlation between a hit segment of TagF and ADC spectrum of Lead Grass measured at May 2004. ADC spectrum of Lead grass depends on TagF segment, that is, photon energy. Dents around TagF15 and TagF46 are due to supports at the window on the accelerator ring. $N_{\text{calorimeter}}$ is estimated from ADC spectrum of Lead grass for each TagF segment.

Figure 3.38 shows tagging efficiencies of each experimental periods. Errors are statistical only. Decreases in efficiencies are found around TagF1-10 (high energy side for photon energy) and TagF35-48 (low energy side). In principle, the efficiencies for each segment should be equal because the photon interaction possibility between radiator and target is almost uniform in present energy region. The effect for high energy side is considered due to the noise trigger which are made by interaction with residual gas in accelerator ring. On the other hand, the effect for low energy side is considered due to supports at the window on the accelerator ring. These effects are not corrected since the situation is the same with normal data taking in any beam intensity.

The $f_{\text{att.}}$ is estimated by calculation from radiation length of materials and by simu-
Figure 3.37: Momentum distribution of events applied invariant mass cut and selected the acceptance Region1 (left) and Region2 (right) in the photon energy region from 0.9 to 1.0 GeV (upper) and from 1.0 to 1.1 GeV (lower). The background contributions (open triangle for leakage from target, diamond for wrong combination) are compared with data (open square).

Table 3.3: The typical value of tagging efficiency for each measurement. The values of 2nd column are the efficiency for tagF segment 1. The values of 3rd column are averaged for tagF from segment 10 to 48.

<table>
<thead>
<tr>
<th>period</th>
<th>minimum</th>
<th>average</th>
</tr>
</thead>
<tbody>
<tr>
<td>September '03</td>
<td>0.73</td>
<td>0.80</td>
</tr>
<tr>
<td>November '03</td>
<td>0.75</td>
<td>0.80</td>
</tr>
<tr>
<td>December '03</td>
<td>0.75</td>
<td>0.80</td>
</tr>
<tr>
<td>April '04</td>
<td>0.74</td>
<td>0.79</td>
</tr>
<tr>
<td>May '04</td>
<td>0.74</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Analysis efficiency

In analysis as mentioned in Sect.3.3, to remove accidental coincidence between TagF and TagB, we apply various cuts for tagger. The effect is defined as tagger analysis efficiency, $\epsilon_{\text{tagana}}$.

The efficiency is estimated using tagger trigger run which is not biased by any condition from NKS side, and calculated from the ratio of number of events before cut to
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Figure 3.38: The typical arrangement for the measurement of tagging efficiency.

Figure 3.39: Correlation between a segment of TagF and ADC spectrum of Lead grass. Upper and right panels show the projection spectrum. Dents around TagF15 and TagF46 are due to supports at the window on the accelerator ring.

those after cut.

Figure 3.41 shows the beam intensity dependence of tagger analysis efficiency. These run was taken at beam intensity of 20 kHz, 130 kHz, 1.2 MHz, 1.8 MHz and 2.7 MHz,
3.10. DIFFERENTIAL CROSS SECTION

Figure 3.40: Tagging Efficiencies measured at each experimental periods.

respectively. Obviously, the efficiencies depend on beam intensity. This is attributed to increase of accidental coincidence. When the cross section is estimated, tagger analysis efficiency is calculated by mean value of normal beam intensity runs for each experimental periods. Typical efficiencies are listed in Table 3.4. These values are averaged from TagF segment 1 to 20. In normal data taking, the fluctuation of beam intensity was within 0.5 MHz. Therefore, the systematic error of the tagger analysis efficiency is ± 3%.

Table 3.4: The typical value of tagger analysis efficiency for each measurement. The values are averaged for tagF from segment 1 to 20.

<table>
<thead>
<tr>
<th>period</th>
<th>average (1 to 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September '03</td>
<td>0.881 ± 0.0024 (stat.)%</td>
</tr>
<tr>
<td>November '03</td>
<td>0.910 ± 0.0008 (stat.)%</td>
</tr>
<tr>
<td>December '03</td>
<td>0.908 ± 0.0008 (stat.)%</td>
</tr>
<tr>
<td>April '04</td>
<td>0.891 ± 0.0013 (stat.)%</td>
</tr>
<tr>
<td>May '04</td>
<td>0.888 ± 0.0018 (stat.)%</td>
</tr>
</tbody>
</table>

3.10.3 Number of target

As mentioned in Sect.2.4, the temperature of the liquid deuterium and the pressure of residual deuterium gas were monitored through experimental period. Thereby, the density of the liquid deuterium can be calculated. Because the fluctuations of the temperature and pressure did not much affect the density, namely amount of deuterium
target. In contrast, the change of the thickness of the target cell due to the pressure of liquid deuterium was larger. The expansion of target cell is calculated by finite element method (FEM) and evaluated about 2 mm for both side. Besides, the thickness of the target during the experiments can be estimated to be 3.3 cm from the vertex points distribution (Fig.3.18). This is consistent with FEM.

In addition, due to the fluctuation of circulating electron beam, the position irradiated photons on the target changed slowly. It was corrected by adjusting the moving position of the radiator, and so the fluctuation of beam position on the target was less than 5 mm. Besides, when the change of circulating electron beam was large, it was corrected by adjusting the orbit of the electron beam with tuning the RF frequency of accelerator. Figure.3.42 shows the dependence of number of deuteron on the position of photon beam and the expanding condition of mylar films. Because beam offset was 5 mm at the maximum in each experimental period, number of deuteron used in analysis are calculated by taking mean value between 0 to 5 mm. Table.3.5 shows typical values (detailed are discussed in Appendix.A).

**DAQ efficiency**

The DAQ efficiency was evaluated from scaler counts for trigger of request and accept. A typical DAQ efficiency was 90 % for a trigger rate of 100 Hz. DAQ efficiencies for each experimental periods are listed in Table.3.6.
Figure 3.42: Number of neutrons for the deuteron density of 0.173 g/cm$^3$. Upper figure shows the schematic view of the target cell. The expansion of mylar films are drawn exaggeratedly. Lower panel shows number of neutrons for each beam offsets and expanding condition. The points correspond to expansion of 3.0, 2.5, 2.0, 1.5, 1.0 mm in order from top.

### 3.10.4 Analysis efficiencies

**Pre-selection efficiency**

Before the tracking search, pre-selections of MLH cut and the angle correlation cut were applied as mentioned in Sect.3.5. The efficiency of the angle correlation cut depends
Table 3.5: The list of number of deuteron. Most largest error is due to uncertainty of the thickness of target.

<table>
<thead>
<tr>
<th>month</th>
<th>density of D$_2$ (g/cm$^2$)</th>
<th>thickness (cm)</th>
<th>number of deuteron (barn$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>0.168 ± 0.001 (stat.)</td>
<td>3.1 ± 0.1 (syst.)</td>
<td>0.168 ± 0.001 ± 0.001</td>
</tr>
<tr>
<td>November ~ May</td>
<td>0.173 ± 0.001 (stat.)</td>
<td>3.1 ± 0.1 (syst.)</td>
<td>0.173 ± 0.001 ± 0.001</td>
</tr>
</tbody>
</table>

Table 3.6: DAQ efficiencies for each month. In the latter half of september, because beam intensity was high, about 2.5~2 MHz, DAQ efficiency was lower than that of other period.

<table>
<thead>
<tr>
<th>month</th>
<th>DAQ efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>September (first half)</td>
<td>90.1 ± 0.04 (stat.)%</td>
</tr>
<tr>
<td>(latter half)</td>
<td>85.1 ± 0.03 (stat.)%</td>
</tr>
<tr>
<td>November</td>
<td>89.4 ± 0.02 (stat.)%</td>
</tr>
<tr>
<td>December</td>
<td>91.7 ± 0.03 (stat.)%</td>
</tr>
<tr>
<td>April</td>
<td>89.8 ± 0.04 (stat.)%</td>
</tr>
<tr>
<td>May</td>
<td>88.1 ± 0.02 (stat.)%</td>
</tr>
</tbody>
</table>

on the kinematics of pion and the geometry of detectors. This efficiency is included in the acceptance correction. Besides, MLH efficiency, $\epsilon_{MLH}$, was estimated by following method. This efficiencies were estimated for every OH segments. We require that number of hits of TagH, IH and OH are 1 in order to select events as clear as possible. Additionally, for the efficiency of left side, we require that the track in Right arm is identified as pion. From these conditions, the triggered particle in the Left side was expected a hadron. The results are shown in Figure 3.43 and listed in Table 3.7.

**Tracking efficiency**

Tracking efficiencies were estimated for every OH segments. The events selection was the same with the selection for MLH efficiency. Nevertheless, in forward and backward direction, there are electrons or positrons which does not through the chamber but hitting IH and OH, so the tracking efficiency is seen relatively low. The tracking efficiencies from OH segment 4 to 12 are nearly flat, then we use the mean value in this

Table 3.7: MLH efficiency for each month. The error is statistic error.

<table>
<thead>
<tr>
<th></th>
<th>September</th>
<th>November</th>
<th>December</th>
<th>April</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>97.7 ± 0.08 %</td>
<td>97.6 ± 0.07 %</td>
<td>97.6 ± 0.05 %</td>
<td>97.6 ± 0.04 %</td>
<td>97.4 ± 0.04 %</td>
</tr>
<tr>
<td>Right</td>
<td>97.7 ± 0.08 %</td>
<td>97.6 ± 0.06 %</td>
<td>97.7 ± 0.05 %</td>
<td>97.4 ± 0.04 %</td>
<td>97.3 ± 0.04 %</td>
</tr>
<tr>
<td>Both</td>
<td>95.5 ± 0.11 %</td>
<td>95.3 ± 0.09 %</td>
<td>95.4 ± 0.07 %</td>
<td>95.1 ± 0.05 %</td>
<td>94.8 ± 0.06 %</td>
</tr>
</tbody>
</table>
Figure 3.43:

Table 3.8: Tracking efficiency for each month. The error is statistic error.

<table>
<thead>
<tr>
<th></th>
<th>September</th>
<th>November</th>
<th>December</th>
<th>April</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>97.40±0.07%</td>
<td>97.40±0.07%</td>
<td>97.38±0.09%</td>
<td>98.06±0.07%</td>
<td>98.00±0.05%</td>
</tr>
<tr>
<td>Right</td>
<td>96.88±0.11%</td>
<td>96.88±0.11%</td>
<td>96.92±0.13%</td>
<td>96.48±0.13%</td>
<td>97.67±0.06%</td>
</tr>
<tr>
<td>Both</td>
<td>94.36±0.13%</td>
<td>94.36±0.13%</td>
<td>94.38±0.15%</td>
<td>94.61±0.14%</td>
<td>95.72±0.07%</td>
</tr>
</tbody>
</table>

region as tracking efficiency. Table.3.8 shows the tracking efficiency for each layers.

**Efficiency of cuts for $\chi^2$ and number of hits in a track**

As mentioned in Sect.3.5, $\chi^2$ cut is applied for both tracks in Left arm and Right arm. Besides, it is required that number of hits in a track are larger than 7 for both tracks. Accordingly, efficiencies for these cuts are estimated. Firstly, efficiency for number of hits, $\epsilon_{\#\text{hits}}$ is estimated, and then efficiency for $\chi^2$ cut, $\epsilon_{\chi^2}$ is estimated.

$$
\epsilon_{\text{goodtrack}} = \epsilon_{\#\text{hits}} \cdot \epsilon_{\chi^2}
$$

$$
\epsilon_{\#\text{hits}} = \frac{N_{\#\text{hits}>7}}{N}
$$

$$
\epsilon_{\chi^2} = \frac{N_{\#\text{hits}>7, \chi^2<8}}{N_{\#\text{hits}>7}}
$$
The results are shown in Fig. 3.45.

Figure 3.45: Efficiency of #hits cut (left) and $\chi^2$ cut (right) for the experimental data.

The systematic error is $\pm 5\%$ accordingly to the dependence of the photon intensity.
3.10.5 Summary of efficiencies

Table 3.9 shows the typical values of efficiencies and its statistical or systematic errors.

Table 3.9: Summary of efficiencies. Each values are averaged (for efficiency) or summed (for $N_i$) of all experimental periods. Normalization from number photons are taken account of averaged values. Systematic errors are estimated from the fluctuations of each experimental period or photon intensity.

<table>
<thead>
<tr>
<th>name</th>
<th>value</th>
<th>statistic error</th>
<th>systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{Gate}$</td>
<td>Gating for timing and invariant mass efficiency</td>
<td>95.42%</td>
<td>$&lt; 0.1%$</td>
</tr>
<tr>
<td>$N_\gamma$</td>
<td>number of hits of TagF from scaler counts</td>
<td>$4.6 \times 10^{12}$</td>
<td>$&lt; 0.1%$</td>
</tr>
<tr>
<td>$N_{target}$</td>
<td>number of target [barn$^{-1}$]</td>
<td>0.172</td>
<td>0.0005</td>
</tr>
<tr>
<td>$\varepsilon_{DAQ}$</td>
<td>Daq efficiency</td>
<td>89.07%</td>
<td>$&lt; 0.1%$</td>
</tr>
<tr>
<td>$\varepsilon_{tagging}$</td>
<td>tagging efficiency averaged 10 to 48</td>
<td>79.1%</td>
<td>$\pm 0.1%$</td>
</tr>
<tr>
<td>$\varepsilon_{tagana}$</td>
<td>tagger analysis efficiency averaged TagF 1 to 20</td>
<td>89.4%</td>
<td>$\pm 0.1%$</td>
</tr>
<tr>
<td>$\varepsilon_{MLH}$</td>
<td>multiplicity cut</td>
<td>95.1%</td>
<td>$&lt; 0.1%$</td>
</tr>
<tr>
<td>$\varepsilon_{tracking}$</td>
<td>tracking efficiency</td>
<td>94.9%</td>
<td>$&lt; 0.1%$</td>
</tr>
<tr>
<td>$\varepsilon_{#hit}$</td>
<td># hits cut in a track</td>
<td>95%</td>
<td>$&lt; 0.1%$</td>
</tr>
<tr>
<td>$\varepsilon_{\chi^2}$</td>
<td>$\chi^2$ cut</td>
<td>95%</td>
<td>$&lt; 0.1%$</td>
</tr>
</tbody>
</table>
Chapter 4

Result

In this chapter, experimental results are presented and compared with theoretical calculations mentioned in Chap. 1. Firstly, the calculation method of cross section on deuteron target is described in 4.2. Finally, experimental results are discussed comparing with the calculations in Sect. 4.3.

4.1 Experimental results

Laboratory angular distribution of the cross sections for $K^0$ after subtraction of background contributions are shown in Fig. 4.1 in the photon energy regions of $0.9 < E_\gamma < 1.0$ and $1.0 < E_\gamma < 1.1$ GeV. As mentioned in Sect. 3.10.1, we select three regions, Reg1, Reg2 and Reg3 on acceptance map. Therefore, the cross sections in Fig. 4.1 are calculated by

$$\frac{d\sigma}{d\Omega} = \int_{E_{\text{min}}}^{E_{\text{max}}} dE_\gamma \int_{\text{Reg1+Reg2+Reg3}} \frac{d\sigma}{dpd\Omega} dp \ [\mu b/sr \cdot GeV].$$

Next, momentum dependence of the cross sections are shown in Fig. 4.2 in the photon energy region of $0.9 < E_\gamma < 1.0$ and $1.0 < E_\gamma < 1.1$ GeV.

$$\frac{d\sigma}{dp} = \int_{E_{\text{min}}}^{E_{\text{max}}} dE_\gamma \int_{\text{Reg1 or Reg2}} \frac{d\sigma}{dpd\Omega} d\cos \theta \ [\mu b/(GeV/c) \cdot GeV].$$
Figure 4.1: Angular distributions of cross section in the photon energy from 0.9 to 1.0 GeV (left) and from 1.0 to 1.1 GeV (right), where square with red error bar is experimental data, triangle with green error bar and diamond with blue error bar are background, leakage from the target and wrong combination, respectively, in upper figures. And lower figures show the results subtracted background contributions. Error bars are overdrawn as (statistic) and (statistic + systematic).
Figure 4.2: Momentum dependence of cross section in the photon energy from 0.9 to 1.0 GeV (left) and from 1.0 to 1.1 GeV (right), and Region 1 (upper group) and Region 2 (lower group) cut, where square with red error bar is experimental data, triangle with green and diamond with blue error bar are background, leakage from the target and wrong combination, respectively. Squares with black error bars are results subtracted background contributions. Error bars are overdrawn as (statistic) and (statistic + systematic).
4.2 Theoretical calculations

We measured the cross section of the inclusive process \(d(\gamma,K^0)\Lambda p\) in laboratory frame. Therefore, inclusive cross section on a deuteron should be calculated and compared with the present results according to the elementary models for kaon photoproduction. Firstly, the phenomenological models used in the present analysis are explained in Sect. 4.2.1. In Section 4.2.2, the way of estimation of the \(K^0\) photoproduction is explained.

4.2.1 Isobar models

As mentioned in Sect. 1.1.2, two theoretical models, Kaon-MAID[36] and Saclay-Lyon A (SLA, [34]), are mainly compared with our data in present analysis.

Kaon-MAID

The Kaon-MAID model is one of the latest isobar models. This includes 4 nucleon resonances and 2 kaon resonances as intermediate state in resonance terms (Table 4.1). The resonance \(D_{13}\), which have not yet discovered experimentally but predicted by the constituent quark model, is added to reproduce the bump structure of the total cross section around \(E_{\text{lab}}^\gamma = 1.5\) GeV taken by SAPHIR[6]. The hadronic form factors are introduced in the model according to the gauge invariant prescription[43].

SLA

The SLA is a simple version of the full Saclay-Lyon model[27], in which the nucleon resonances with spin \(-\frac{1}{2}\) and \(\frac{5}{2}\) are excluded. The resonances included are 1 nucleon resonance, 2 kaon resonances and 4 hyperon resonances (Table 4.1).

| Table 4.1: Resonances included in Kaon-MAID and Sacray-Lyon A. |
|--------------------------|---------------------|-------------------|-------------------|
| model                   | s-channel           | t-channel         | u-channel         |
| Kaon-MAID               | \(S_{11}(1650)\), \(P_{11}(1710)\), \(P_{13}(1720)\), \(D_{13}(1895)\) | \(K^*(892), K_1(1270)\) | none              |
| SLA                     | \(P_{13}(1720)\)    | \(K^*(892), K_1(1270)\) | \(\Lambda(1405), \Lambda(1670)\)  |
|                         |                     |                   | \(\Lambda(1810), \Sigma(1660)\) |

4.2.2 Calculation of \(K^0\) photoproduction

The elementary cross section

The parameters in the isobar models are constrained by some symmetries. As mentioned in Sect. 1.1.2(Eq. 1.1.1.2), SU(3) symmetry limits the main coupling constants,\(-4.5 < g_{K\Lambda p}/\sqrt{4\pi} < -3.0\) and \(0.9 < g_{K\Sigma^0 p}/\sqrt{4\pi} < 1.3\).

Table 4.2 shows the particles associated each vertexes in Feynman diagrams. The
Table 4.2: Associated particels at vertices except for Born terms. For each reaction, associated to photo-couplings are listed in the upper section, and hadronic couplings are listed in the lower section.

<table>
<thead>
<tr>
<th>reaction</th>
<th>s-channel</th>
<th>t-channel</th>
<th>u-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p(\gamma, K^+)\Lambda$</td>
<td>$N^{*+}_{\gamma \gamma}$</td>
<td>$(K^{<em>+}K^+\gamma), (K^{</em>+}_{1}K^+\gamma)$</td>
<td>$(\Lambda^{*}\Lambda\gamma), (\Sigma^{0}\Lambda\gamma), (\Sigma^{0}\Lambda\gamma)$</td>
</tr>
<tr>
<td></td>
<td>$K^+\Lambda N^{*+}$</td>
<td>$(K^{<em>+}\Lambda p), (K^{</em>+}_{1}\Lambda p)$</td>
<td>$(K^+\Lambda^* p), (K^+\Sigma^0 p), (K^+\Sigma^{*0} p)$</td>
</tr>
<tr>
<td>$n(\gamma, K^0)\Lambda$</td>
<td>$N^{*0}_{\gamma \gamma}$</td>
<td>$(K^{*0}K^0\gamma), (K^{*0}_{1}K^0\gamma)$</td>
<td>$(\Lambda^{*}\Lambda\gamma), (\Sigma^{0}\Lambda\gamma), (\Sigma^{*0}\Lambda\gamma)$</td>
</tr>
<tr>
<td></td>
<td>$K^0\Lambda N^{*0}$</td>
<td>$(K^{*0}\Lambda n), (K^{*0}_{1}\Lambda n)$</td>
<td>$(K^0\Lambda^* n), (K^0\Sigma^0 n), (K^0\Sigma^{*0} n)$</td>
</tr>
</tbody>
</table>

Fitting parameters of coupling constants are the main coupling, $g_{K\Lambda p}, g_{K\Sigma^0 p}$, and the products of photo-coupling and hadronic coupling for s-/u-/t/channels. For example, a coupling parameter $G_{N^*} = g_{N^*N^*} \cdot g_{K\Lambda N^*} / \sqrt{4\pi}$ for s-channel.

When the elementary cross section of $K\Lambda$ channel (or a certain isospin channel) is calculated, we assume the isospin symmetry for hadronic coupling constants,

$$
g_{K^+\Lambda p} = g_{K^0\Lambda n}$$

$$g_{K^+\Sigma^0 p} = -g_{K^0\Sigma^0 n} = \frac{g_{K^0\Sigma^0 p}}{\sqrt{2}} = \frac{g_{K^0\Sigma^0 n}}{\sqrt{2}}$$

$$g_{K^+\Sigma^0\Delta^+} = g_{K^0\Sigma^0\Delta^0} = \sqrt{2} g_{K^0\Sigma^0\Delta^+} = \sqrt{2} g_{K^0\Sigma^0\Delta^-}$$

Following [44], helicity amplitudes given by the Particle-Data-Group[45] can be written in terms of electromagnetic coupling constants for resonances. For spin-$\frac{1}{2}$ resonances only magnetic transition is possible, and for spin-$\frac{3}{2}$ resonances two couplings can contribute.

$$\frac{g_{N^{*0}_{\gamma \gamma}}}{g_{N^{*+}_{\gamma \gamma}}} = \frac{A^N_{1/2}}{A^p_{1/2}} \quad \text{(for spin-$\frac{1}{2}$)}$$

$$\begin{align*}
g^{(1)}_{N^{*0}_{n n^*}} & = \sqrt{3} A^N_{1/2} \pm A^p_{3/2} \\
g^{(1)}_{N^{*0}_{p n^*}} & = \sqrt{3} A^p_{1/2} \pm A^p_{3/2} \\
g^{(2)}_{N^{*0}_{n n^*}} & = \sqrt{3} A^N_{1/2} - (m_N/m_{N^*}) A^N_{3/2} \\
g^{(2)}_{N^{*0}_{p n^*}} & = \sqrt{3} A^p_{1/2} - (m_N/m_{N^*}) A^p_{3/2}
\end{align*}$$

where $A^N_s$ means the helicity amplitude of nucleon(N) with spin-$s$.

From the relations above, the couplings in s-channel and u-channel can be converted from $K^+\Lambda$ to $K^0\Lambda$ channel.

On the other hands, it is not so easy for t-channel diagrams. The decay width of kaon resonances are written as following formula,

$$\Gamma_{K^*\rightarrow K\gamma} = \frac{1}{24} \frac{|g_{K^*K\gamma}|^2}{4\pi M^2} \left( m_{K^*} \left( 1 - \frac{m_K^2}{m_{K^*}^2} \right) \right)^3$$

where $K^*$ means $K^*$ and $K_1$, and $M = 1$ GeV is normalized factor to make $g_{K^*K^*}$
4.2. THEORETICAL CALCULATIONS

Dimensionless. For both charged and neutral $K^*$, the decay widths are well known[45];

$$r_{K^*K\gamma} = \frac{g_{K^*+K^+\gamma}}{g_{K^*0K^0\gamma}} = -\sqrt{\frac{\Gamma_{K^*+\to K^+\gamma}}{\Gamma_{K^*0\to K^0\gamma}}} = -1.53$$

where the sign is decided from the quark model prediction. However since the decay widths of $K_1$ are not well known, these are free also parameters to be derived by data. For Kaon-MAID, since the set of parameters were fitted simultaneously by the $K^+\Lambda$, $K^+\Sigma^0$ and $K^0\Sigma^+$ data, it can predict the $K^0$ photoproduction under conditions mentioned above. The ratio $r_{K_1K\gamma}$ was decided to $-0.4474$ by fitting the $K\Sigma$ data.

For SLA, however, the parameters were adjusted from only $K^+\Lambda$ production data, and so the ratio of the charged and neutral $K_1$ ($r_{K_1K\gamma}$) could not be decided. Therefore, when the calculation of the $K^0$ photoproduction using SLA is carried out, $r_{K_1K\gamma}$ is considered as free parameter.

The differential cross section on the deuteron target

The differential cross section of $K^0$ photoproduction on the deuteron target is calculated by Bydzovský et al using a simple model based on the impulse approximation in which a proton acts as a spectator[46]. The reason why this approach neglects the final state interaction (FSI) is justified by following. Since the parameters are decided from $K^+\Xi$ production on proton, the FSI of $K\Lambda$ is inserted in the coupling constants of the elementary amplitude. Besides KN interaction is weak on the hadronic scale. In addition, the $\Lambda N$ interaction is not so important for the inclusive $d(\gamma,K^+)\Lambda n$ reaction near the threshold[47], and the nature of the FSI in the $K^+$ and $K^0$ production is considered not so different.

The kinematics to be calculated is

$$\gamma(P_\gamma, \lambda) + d(P_d, \mu) \to K(P_K) + \Lambda(P_\Lambda, \eta') + N'(P_N', \xi')$$

where $P$’s are 4-momenta and $\lambda, \mu, \eta', \xi'$ are spin of each particles.

Then, the first-order of the $S$-matrix is

$$S_{fi} = i(2\pi)^4\delta^4(P_f - P_i)M_{fi}\left(\frac{1}{2E_\gamma V}\right)\left(\frac{1}{2E_d V}\right)\left(\frac{1}{2E_K V}\right)\left(\frac{m_\Lambda}{E_\Lambda V}\right)\left(\frac{m_N'}{E_{N'} V}\right)$$

where $P_i = P_\gamma + P_d$ and $P_f = P_K + P_\Lambda + P_N'$. The cross section in a general reference frame is

$$d^9\sigma = \frac{1}{6} \sum_{\text{spin}} |S_{fi}|^2 \frac{d^3p_K V d^3p_\Lambda V d^3p_{N'} V}{(2\pi)^3(2\pi)^3(2\pi)^3} / (T v_{\text{rel}} / V)$$

$$= \frac{1}{(2\pi)^5} \frac{m_\Lambda m_{N'}}{8P_\gamma \cdot P_d E_\Lambda E_{N'}} \delta^4(P_f - P_i) \frac{1}{6} \sum_{\text{spin}} |M_{fi}|^2 d^3p_K d^3p_\Lambda d^3p_{N'}$$

where the factor $1/6$ arises from spin average of incident photon and deuteron. Up to here, it is general formula.
In the *spectator approximation* it can be written as

\[
d^3\sigma = \frac{1}{(2\pi)^5} \frac{m_{\Lambda}m_{N'}}{8P_\gamma \cdot P_d E_K E_\Lambda E_{N'}} \int d^4P_N \delta^4(P_f^e - P_i^e) 4\pi \frac{(s - m_{N'}^2)^2}{m_{\Lambda}m_N} \frac{d\sigma^e}{dt} \times \delta^4(P_d - P_N - P_{N'}) \frac{1}{4} \sum_{f'j'} |M_{f'i}|^2 d^3P_K d^3P_N d^3P_{N'},
\]

where the integrated value of $P_N$ is the four-momentum of the target, the $\delta$ function is separated into two parts, and the separated elementary cross section

\[
\frac{d\sigma^e}{dt}(s, t) = \frac{1}{4\pi} \frac{m_{N'}m_{\Lambda}}{(s - m_{N'}^2)^2} \frac{1}{4} \sum_{f'j'} |M_{f'i}|^2
\]

is introduced. The $s = (P_d + P_N)^2$ and $t = (P_\gamma - P_K)^2$ are the Mandelstam variables.

After expressing the matrix element $M_{f'i}$ via $M_{f'i}^2$ (derived in [48]), that is

\[
\frac{1}{6} \sum_{f'j'} |M_{f'i}|^2 = (2\pi)^3 \frac{2m_d E_N}{E_N} \frac{1}{4} \sum |M_{f'i}|^2 u_d(p_{N'})^2,
\]

and some algebra, the expression for the differential cross section in the laboratory frame is

\[
\frac{d^3\sigma}{d|\vec{p}_K|d\Omega} = \frac{m_{N'}(s - m_{N'}^2)^2}{4m_N E_\gamma E_K E_N |\vec{p}_\gamma - \vec{p}_K|} \frac{u_d(p_{N'})^2}{\pi} \frac{d\sigma^e}{dt} d|\vec{p}_N| d\Phi_{N'}.
\]

where $\Phi$ is the azimuthal angle of the spectator nucleon. The isospin formalism, $m_n = m_p$, is assumed and the isospin factor $\sqrt{2}$ is produced to take account of the antisymmetrization of two nucleons in the intermediate state. The energy of the target nucleon is given by $E_N = E_d - E_{N'} = E_K + E_\Lambda - E_\gamma$, for off-shell approximation and by $E_N = \sqrt{m_N^2 + \vec{p}_N^2}$ for on-shell approximation, and the target nucleon mass is taken to be consistent with kinematics, $m_N = \sqrt{P_N^2}$, $\vec{p}_N = -\vec{p}_{N'}$.

In this calculations non relativistic Bonn OBEPQ deuteron wave function[49] is used to the neutron distribution.

### 4.3 Comparison and discussion

Figure 4.3 show the relation NKS acceptance region to the kinematical distribution using Kaon-MAID and SLA($r_{K1K\gamma} = -1.6$). For higher photon energy, the kinematical region tends to avoid the acceptance region of NKS. The Region 1 covers more than 97% of the area $0.9 \leq \cos \theta_{\text{Lab}} < 1.0$ However the efficiency of the Region 2 extremely changes with photon energy.

**Angular distribution**

Figure 4.4 show the angular distribution in laboratory frame and the results of the theoretical calculation are also overdrawn. The rugged structures of the theoretical
Figure 4.3: Comparison the effective region of NKS acceptance and theoretical calculations, Kaon-MAID (left) and SLA($r_{K_1K\gamma} = -1.6$) (right). Red lines represent the accepted region. The values mean the efficiencies of Region 1 and 2.

calculations is due to the selection of the region on the acceptance map of NKS. The region cuts are also applied to the theoretical calculations. For the photon energy region from 0.9 to 1.0 GeV, the amplitude of Kaon-MAID and SLA($r_{K_1K\gamma} = -2.0$ or $-3.0$) are consistent with our data. However for the region from 1.0 to 1.1 GeV, the estimation from Kaon-MAID is too large.

Momentum dependence

Figure 4.5 show the momentum dependence in the laboratory frame and the results of the calculations are also overdrawn. Although for the photon energy region from 0.9 to 1.0 GeV Kaon-MAID and SLA($r_{K_1K\gamma} = -2.0$) contribute the almost consistent results with data, for the region from 1.0 to 1.1 GeV the calculations give overestimation at the higher momentum region.

From fig. 4.3, in the higher photon energy region, since the peak of the yield distribution crosses the edge of the effective acceptance region, the spectrum is easily influenced by any conditions, e.g. the resolution of $K^0$ kinematics or photon energy. Therefore a reliable comparison may be performed only at Region 1 at photon energies from 0.9 to 1.0 GeV. Additionally, the contributions from $\gamma d \rightarrow K^0\Sigma^+ p$ or $\gamma d \rightarrow K^0\Sigma^0 n$ processes are negligibly small in the photon energy below 1.0 GeV.

At Region 1 at photon energy from 0.9 to 1.0 GeV, Kaon-MAID and SLA with $r_{K_1K\gamma}$ of about 2 seem to explain the magnitude of the data. However, the shape of the momentum spectrum from Kaon-MAID is larger at higher momentum than that of data, and the shape from SLA is more consistent with data if $r_{K_1K\gamma} = -2.0$. Therefore,
The $\chi^2$ function calculated as follows

$$\chi^2 = \frac{1}{\#\text{data} - 1} \sum_i \left( \frac{(d\sigma/dp)^{th} - (d\sigma/dp)^{exp}}{\Delta(d\sigma/dp)^{exp}} \right)^2.$$ 

The results are shown in fig. 4.6. The $\chi^2$ of SLA show the minimum value at $r_{K_1K_\gamma} \sim -2.0$. Even for the other regions, the $\chi^2$ of SLA is minimum at $r_{K_1K_\gamma} = -2.0 \sim -2.5$ and these are better than Kaon-MAID.

Figure 4.7 shows the elementary differential cross section in CM system using Kaon-MAID and SLA with various $r_{K_1K_\gamma}$ at photon energy of 0.95 and 1.05 GeV.

From fig. 4.7, the amplitude from SLA is minimized and the angular distribution in CM is changed from the backward peak to the 90 degree peak around $r_{K_1K_\gamma} = -2.0 \sim -2.5$. 

Figure 4.4: Laboratory angular distribution of the data and the calculations in Region 1 to 3. The lines represent the calculations using Kaon-MAID (solid), SLA($r_{K_1K_\gamma} = -1.6$, dotted), SLA($r_{K_1K_\gamma} = -2.0$, dashed), SLA($r_{K_1K_\gamma} = -2.5$, solid) and SLA($r_{K_1K_\gamma} = -3.0$, dash-dotted). Since these values are averaged each 0.02 bin and connected by line. Error bars are overdrawn as (statistic) and (statistic + systematic).
4.3. COMPARISON AND DISCUSSION

Figure 4.5: Momentum dependence after corrected efficiencies. Left panels are Region 1 and right panels are Region 2. The photon energy range is 0.9 < $E_\gamma$ < 1.0 (upper) and 1.0 < $E_\gamma$ < 1.1 (lower). Background from case 1 and case 2 are subtracted. Error bars are overdrawn as (statistic) and (statistic + systematic).

Figure 4.6: The values of the $\chi^2$ function which was calculated for the non-zero data points at Region 1 at photon energy from 0.9 to 1.0 GeV. The horizontal axis mean the value of the $r_{K\gamma}$ for SLA. The $\chi^2$ of Kaon-MAID is plotted at 0.
Figure 4.7: The angular distribution of differential elementary cross sections in CM system of $K^0$ photoproduction using Kaon-MAID and SLA with some values of $r_{K_1K_\gamma}$ in photon energy region from 0.9 to 1.0 GeV (upper) and from 1.0 to 1.1 GeV (lower). For SLA, a value in bracket means $-r_{K_1K_\gamma}$. When $-r_{K_1K_\gamma} \leq 2.5$, the distribution become backward peak.
Chapter 5

Conclusion

For the investigation of the strangeness photoproduction, the $n(\gamma, K^0)\Lambda$ reaction has very important and unique feature.

We have measured the $K^0$ photoproduction on a deuteron in the threshold region followed by the measurement of quasi-free process using carbon target. The experiment was carried out at Laboratory of Nuclear Science, Tohoku University which provided tagged photon beam in the region of threshold energy from 0.8 to 1.1 GeV. The $K^0$s were detected by Neutral Kaon Spectrometer via $\pi^+\pi^-$ decay channel. The deuteron target system was constructed and the deuteron density had been kept in stable.

Although the acceptance of NKS limited the effective area of $K^0$ kinematical region, the angular and momentum distributions were obtained and compared with the latest two theoretical model calculations. The calculation was carried out by Bydžovský et al in the spectator approximation using the realistic deuteron wave function to neutron target. Although Kaon-MAID can be calculate the $K^0\Lambda$ channel in its framework, SLA model has free parameter ($r_{K_1K\gamma}$) for the $K^0\Lambda$ channel. Therefore, the calculation was carried out by SLA using various $r_{K_1K\gamma}$. Both models could roughly explain the magnitude and the shape of the data. However, the most reasonable calculation was provided by SLA with $r_{K_1K\gamma} = -2.0 \sim -2.5$. This result implies that the angular distribution of $K^0$ in CM system is backward peak.
Acknowledgement

\(^o^)/^-^- < Thank you
Appendix A

Liquid deuterium

number of neutron is estimated as following formula

\[ N = \int L(x,y)\rho_n I(x,y)dS \]

\[ L(x,y) = \text{WidthOfCell} + 2 \times (\sqrt{l^2 - (x^2 + y^2)} - l + d) \]

\[ l = \frac{d^2 + \text{RadiusOfCell}^2}{d^2} \]

\[ I(x,y) = \frac{1}{2\pi\sigma^2} \exp \left( -\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2} \right) \]

\[ \rho_n = \frac{N_A}{M_{D_2}} \times 2 \times \rho_{D_2} \ [cm^{-3}] \]

\[ N_A = 6.02 \times 10^{23} \ [mol^{-1}] , \ M_{D_2} = 2.014 \times 2 \ [g/mol] \]

\[ \text{WidthOfCell} = 30mm , \ \text{RadiusOfCell} = 40mm \]

\[ \sigma = 5mm \]

\[ \rho_{D_2} = 0.168 , \ 0.173 \ [g/cm^3] \]

\[ y_0 = 0 \]

\[ x_0 = 0 \sim 10mm \ \text{by} \ 1mm \]

\[ d = 1.0 , 1.5 , 2.0 , 2.5 , 3.0mm \]
Bibliography


